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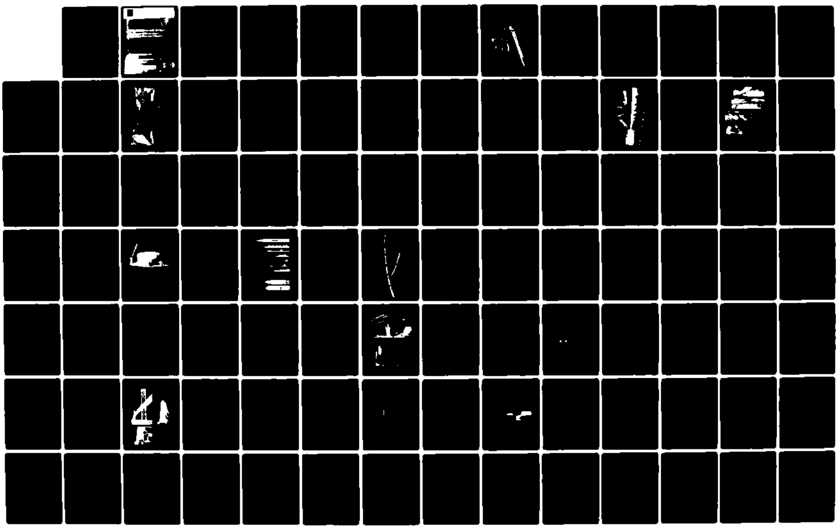

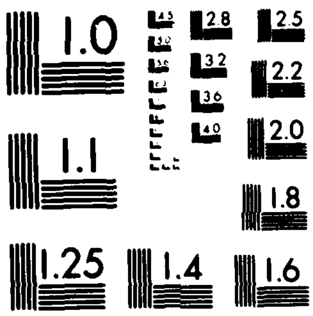

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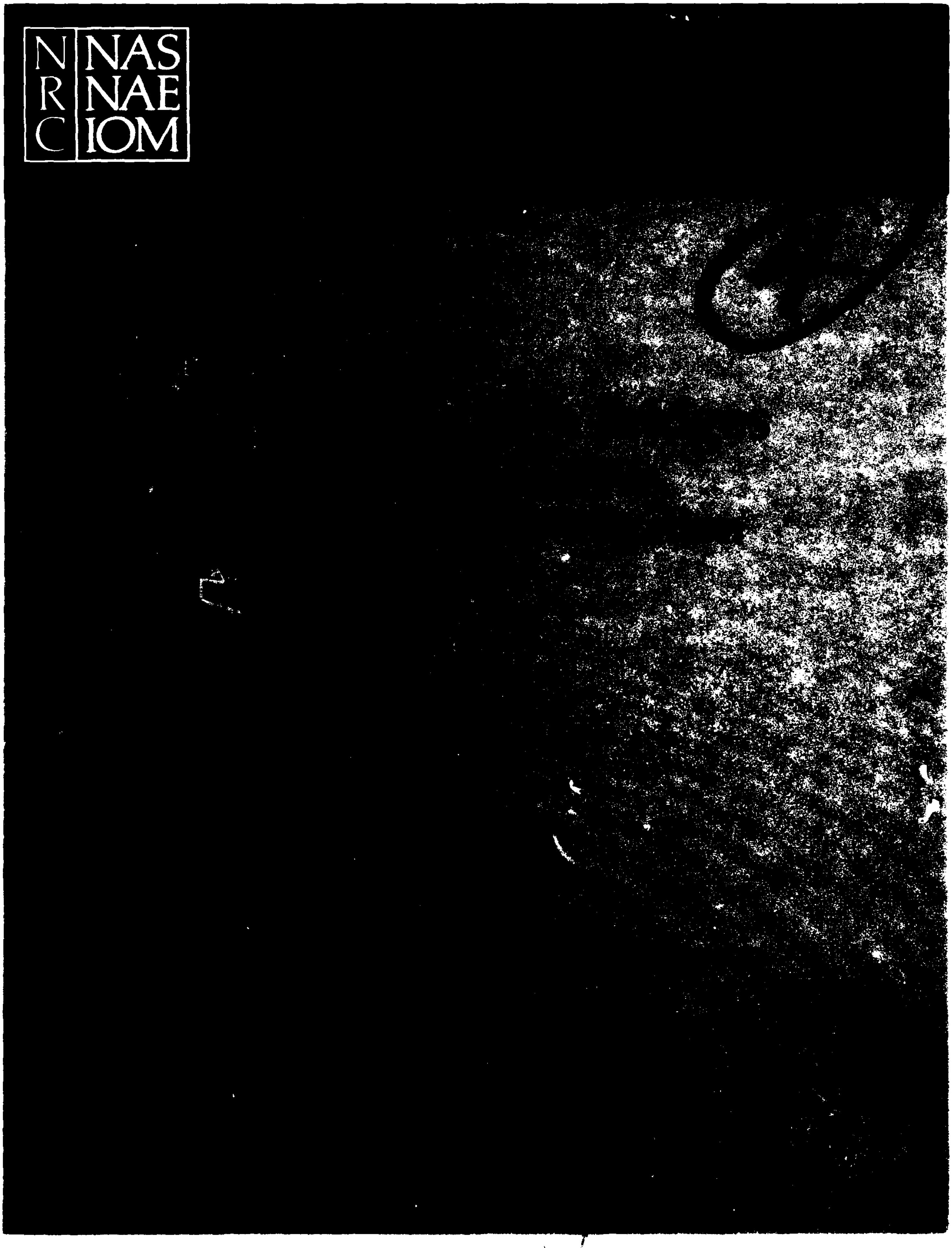
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Ship Collisions with Bridges

The Nature of the Accidents, Their Prevention and Mitigation

Committee on Ship-Bridge Collisions
Marine Board
Commission on Engineering and Technical Systems
National Research Council

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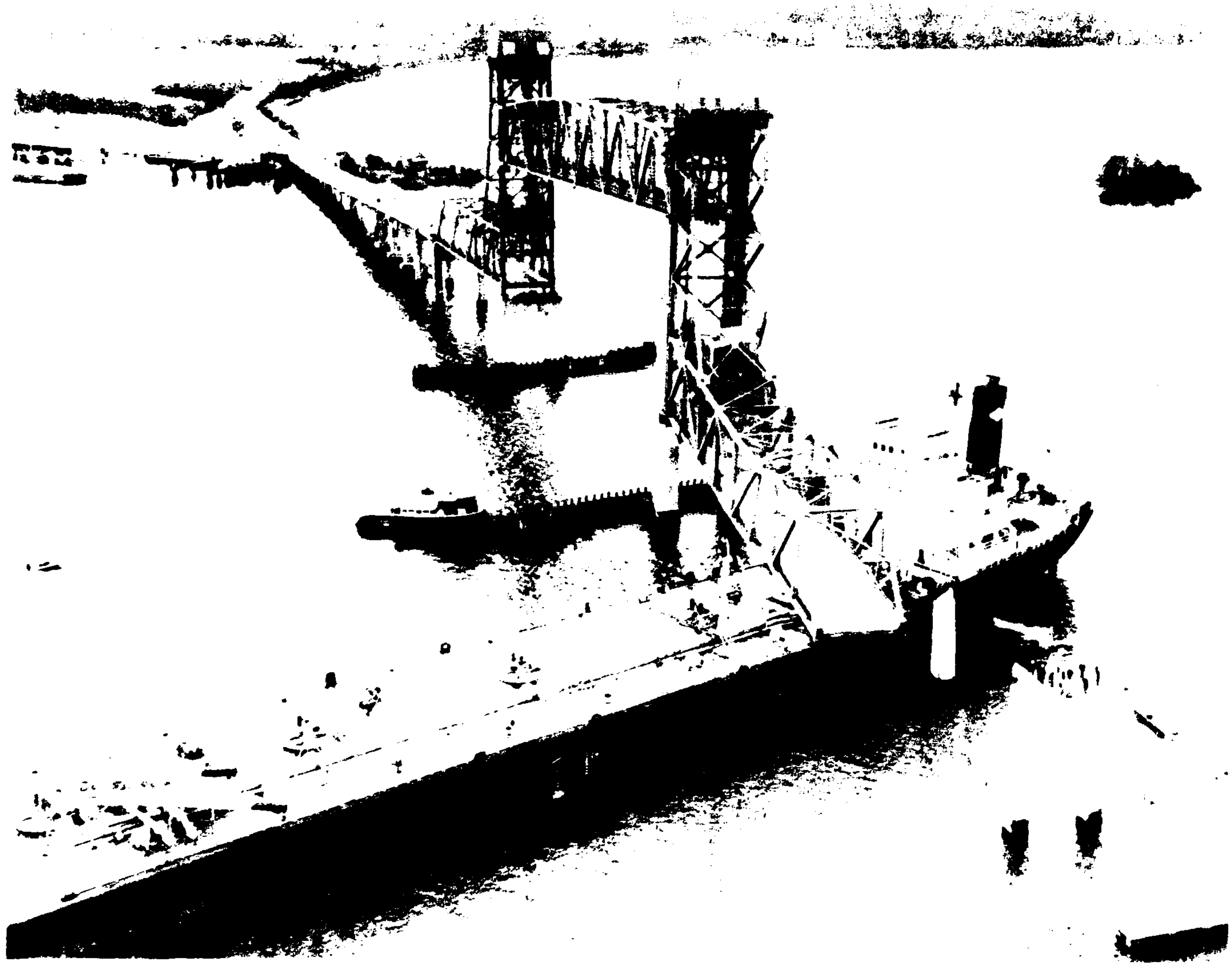

Collision of _Marine Floridian_ and Benjamin Harrison Bridge, Virginia

Photograph: Ken Soper, Virginia Department of Transportation

PREFACE

A possibility not addressed by national policy or engineering standards in the United States is that a bridge may collapse from the impact of a striking ship. The possibility is actual: in the past 20 years, more than 100 lives have been lost in 22 catastrophic ship collisions with bridges. More than 50 of these fatalities occurred in the United States.

Background of the Study

A long-standing concern of the Marine Board of the National Research Council is the application of systematic analysis and engineering to ensure the safety of the public, of navigation, and of the marine environment. Initial investigation of the problem of ship-bridge collisions indicated to the Marine Board that the frequency of such accidents and the severity of their consequences might well be increasing and that the division of responsibilities for navigational projects and bridges among federal and other agencies of government fragments the focus necessary to systematic prevention or mitigation. The Marine Board determined that the subject should be independently assessed and, in accordance with the terms of its charter, that the Marine Board should undertake the study on its own initiative. The Committee on Ship-Bridge Collisions--composed of experts on bridge design and protective systems; navigational aids; and the nature, behavior, and handling of vessels--was appointed by the National Research Council to conduct the study under the direction of the Marine Board.

Scope and Methods of the Study

The Committee on Ship-Bridge Collisions reviewed the nature and scope of the problem in the United States, existing knowledge of ship-bridge collisions, pertinent regulatory and institutional considerations, and mitigation strategies. The study was restricted to bridges spanning major coastal ports and navigational channels of the United States, and to accidental impacts. The St. Lawrence Seaway and Great Lakes were excluded, as well as most of the inland waterways.

International studies of ship-bridge collisions and investigations in foreign countries were being conducted when the committee undertook its assessment. The committee maintained an active exchange of information with these other studies through its foreign member. The committee reviewed the literature (including accident data and reports) pertinent to ship-bridge collisions and consulted with federal authorities and other experts. Three meetings were convened by the committee, including one in Tampa, Florida, to inspect the damaged Sunshine Skyway Bridge and to hear briefings about the several efforts proposed or under way to improve the safety of the replacement bridge and of marine traffic in Tampa Bay. Associations of ship pilots were surveyed to gain an understanding of troublesome ship-bridge problems and to learn the views of those who steer vessels through navigational channels and bridges.

Findings from these phases of the study were addressed by members of the committee from their individual and collective expertise and judgment.

The report represents the consensus of the committee.

Acknowledgments

The Committee on Ship-Bridge Collisions gratefully acknowledges the participation and cooperation in this study of the Federal Highway Administration, U.S. Coast Guard, U.S. Army Corps of Engineers, American Railway Engineering Association, American Association of State Highway and Transportation Officials, and the International Association for Bridge and Structural Engineering.

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EXECUTIVE SUMMARY

Catastrophic bridge accidents are rare, but the number and severity of those due to ship collisions far exceed those due to winds, waves, and earthquakes combined. In the past 20 years, 22 serious ship-bridge collisions worldwide have caused great economic losses because of the closing of waterways for removal of wreckage, severed bridge connections, repairs and replacements, and, most importantly, the loss of more than 100 lives. The majority of these accidents occurred in the United States.

Bridge design criteria have been developed that address performance in seismic activity and resistance to winds that would stop traffic, but no criteria have been developed for withstanding the impacts of ships, which are far more common.

At the request of the Marine Board of the National Research Council, the Committee on Ship-Bridge Collisions examined the risks and consequences of ship collisions with bridges spanning navigable coastal waters, and considerations important to the understanding of these accidents, the interactions of ships and waterways, and measures that can be taken to prevent ship-bridge collisions and to reduce their consequences. The scope of the study encompasses 133 bridges--highway, railroad, and a combination of the two.

Frequency of Ship-Bridge Collisions

The annual occurrence of ship-bridge collisions worldwide increased from 0.5 between 1960 and 1970 to 1.5 between 1971 and 1982. These figures are for serious collisions only--those that completely or partially destroyed the bridge. Many of the bridges suffering a serious collision had been struck repeatedly by vessels.

Ships

In recent years, the sizes of ships plying the waterways have grown dramatically. Further increases are limited primarily by channel depths. Large, fully loaded ships with very little underkeel clearance

represent the potential for the highest impact forces on bridge structures, and they are difficult to maneuver and stop. Ships riding in ballast, or ships that have a large "sail area," such as containerships, are particularly sensitive to wind and wind gusts, and may wander far outside the navigational channel. In 19 serious ship-bridge collisions worldwide that were subsequently investigated, 13 bridges were struck in the approach piers or side superstructure (or both) and only 6 in the main piers.

Dynamics of Ship Collisions

Analysis of collision forces has been carried out by European and Japanese investigators, but these studies are not as yet complete. The impact forces depend on the available kinetic energy of the ship and time interval over which the impact takes place. The kinetic energy of the ship varies with the displacement of the ship and the square of its velocity. For ships with small underkeel clearance, most of this energy will be dissipated in a major collision, even if the impact is oblique. The speed a ship maintains in a channel cannot always be arbitrarily reduced, since headway may be needed for control of the ship, and some diesel ships have a minimum operating speed.

The duration of impact depends on the stiffness and crushability of both the ship and the bridge structure. The longer this interval, the smaller will be the maximum impact force. The impact will be spread out by deformation and crushing of the ship structure, the pier structure, and the soil supporting the pier. Detailed analysis of this complicated interaction will need to address the complicated elastic-plastic behavior of all these elements and will probably require large-scale finite-element techniques. No such analyses appear to have been performed.

Siting and Design of Bridges

Consideration needs to be given to universal and local problems of navigation in the siting and design of bridges, and to reducing the risk of ship collisions. Preference should be given to sites remote from bends, turns, or narrow sections of the navigational channel, to spans that provide greater clearances than the width of the navigational channel, to redundant structural systems, and to location of the main piers on land, if possible, and if not, to location on artificial islands or in very shallow water.

Within other engineering constraints, bridge piers should be as massive as possible and configured to engage a colliding ship in an enlarged footing block or solid wall. Because pier shafts have proved particularly vulnerable to ship collision, they should be reinforced by methods used for offshore structures. The restrainers used to prevent the spans' falling off in earthquakes should be considered, as very similar failure has been observed in ship collisions with bridges.

Bridges over navigable waterways need to be designed to preclude or withstand collisions of vessels. This entails analyzing the risks

posed by vessels and selecting appropriate structural designs, protective devices, or both.

Geotechnical Aspects

Bridge piers absorb lateral impact energy by displacement and tilting that must ultimately be resisted by the soil. If the collision forces are small, the soil responds pseudoelastically: the pier moves a short distance and returns. Larger forces will cause larger inelastic deformations (strains): a significant portion will be permanent. For bridge piers founded on pilings, care must be taken in the design to develop the full load capacity of the piles and their connections for maximum resistance to impact forces.

Adequate scour protection needs to be provided for all bridge piers in water and must be regularly inspected and maintained.

Protective Systems

Bridge piers may be protected from ship collisions by independent structures such as artificial islands, structural barriers, dolphins and protective cells, and moored pontoons. (Moored cable arrays have also been proposed and tried, but neither their protective capability nor the hazards they present--of snapped cables, for example--are well understood.) Devices may alternatively (or additionally) be attached to the bridge piers themselves, principally the many types of fender systems, or sliding blocks of large mass. The choice of systems is site-specific and depends on an analysis of several factors--among them, whether consideration will be given to protecting the vessel as well as the bridge from damage.

Preventive Systems

Analyses of marine accidents indicate three groups of causal factors: shipboard, external, and environmental. For ship-bridge collisions, the critical items in each of these groups are:

<u>SHIPBOARD</u>

- Pilot and master qualifications, training, experience
- Onboard navigational aids
- Inspection and maintenance of onboard instrumentation, communications, navigational and critical engineering equipment

<u>EXTERNAL</u>

- Bridge and waterway design factors
- Traffic engineering measures
- Design and maintenance of aids to navigation

ENVIRONMENTAL

- o Collection, transmission, and presentation of critical information concerning weather, hydrography, etc.

Among the actions that could be taken to increase the margin of safety in each of these areas is to strengthen the required qualifications for licensed marine personnel, with attention to training and to the use of performance standards. The requirements that ships be handled by experienced local pilots could be made more extensive as well as uniform. All-weather, precision navigational systems are operational in many ports of other countries and have been tried experimentally in the United States. The systems may be integrated with bridge operation for motorist warning. Many are portable and can be carried aboard by pilots.

Bridges need to be well marked and lighted. The location and appearance of the bridge relative to the vessel may serve as an aid or a hazard to navigation. The system of aids to navigation in the waterway needs to give maximum guidance to pilots to enable them to line up before and after transiting the bridge; thus the design of the system will have to be site-specific. Buoys, daymarks, ranges, racons, and beacons or sector lights may be used to advantage in increasing the navigability of the waterway with respect to overwater bridges. Systematic analyses to determine the design of the aids-to-navigation system may reveal needs for traffic management in the channel as well.

Navigation can be very much enhanced by the provision of accurate and timely information about the physical environment, such as weather, tides, currents, and water depths throughout the waterway.

Motorist warning systems are being evaluated by the Federal Highway Administration (FHWA), and by some state departments of transportation. The continuation of traffic after a span has been lost to ship collision has caused the greatest loss of life in ship-bridge collisions in the United States and worldwide. Railroad bridges are equipped with automatic, fail-safe mechanical signals that are activated by bridge interruption. Some similar system, according to early results of the FHWA investigation, appears advisable for high-risk highway bridges.

Estimation of Risk and Evaluation of Mitigating Alternatives

Because catastrophic events are rare, the amount of data for estimating the risk of occurrence is small. Much can be learned from a multidisciplinary, multicausal investigation of these rare events. Such an analysis is now required in the United States for all marine accidents resulting in fatalities. Several formal techniques have been developed to estimate and analyze the risk of accidents in complex systems. A few of these have been applied to the risk of ship collisions for specific bridges worldwide, but for just one bridge in the United States (the replacement of the Sunshine Skyway Bridge). The techniques that might be applied are failure modes and effects analysis, logic

diagramming (fault trees and event trees, or chains of sequences), and consequent evaluation. While uncertainty may accompany probabilistic assessments, the application of these techniques can clarify accident scenarios, pinpoint vulnerabilities, define the sequences of events leading to accidents, and indicate the magnitude of the consequences. It will also suggest strategies to reduce the risks and the severity of the consequences.

The value of this type of analysis is that it indicates courses of action that can be taken to enhance safety and sets them out for comparison and decision. If the elements of cost and benefit are reasonably well known (and expressible in the same units), cost-benefit analysis may clarify the comparison.

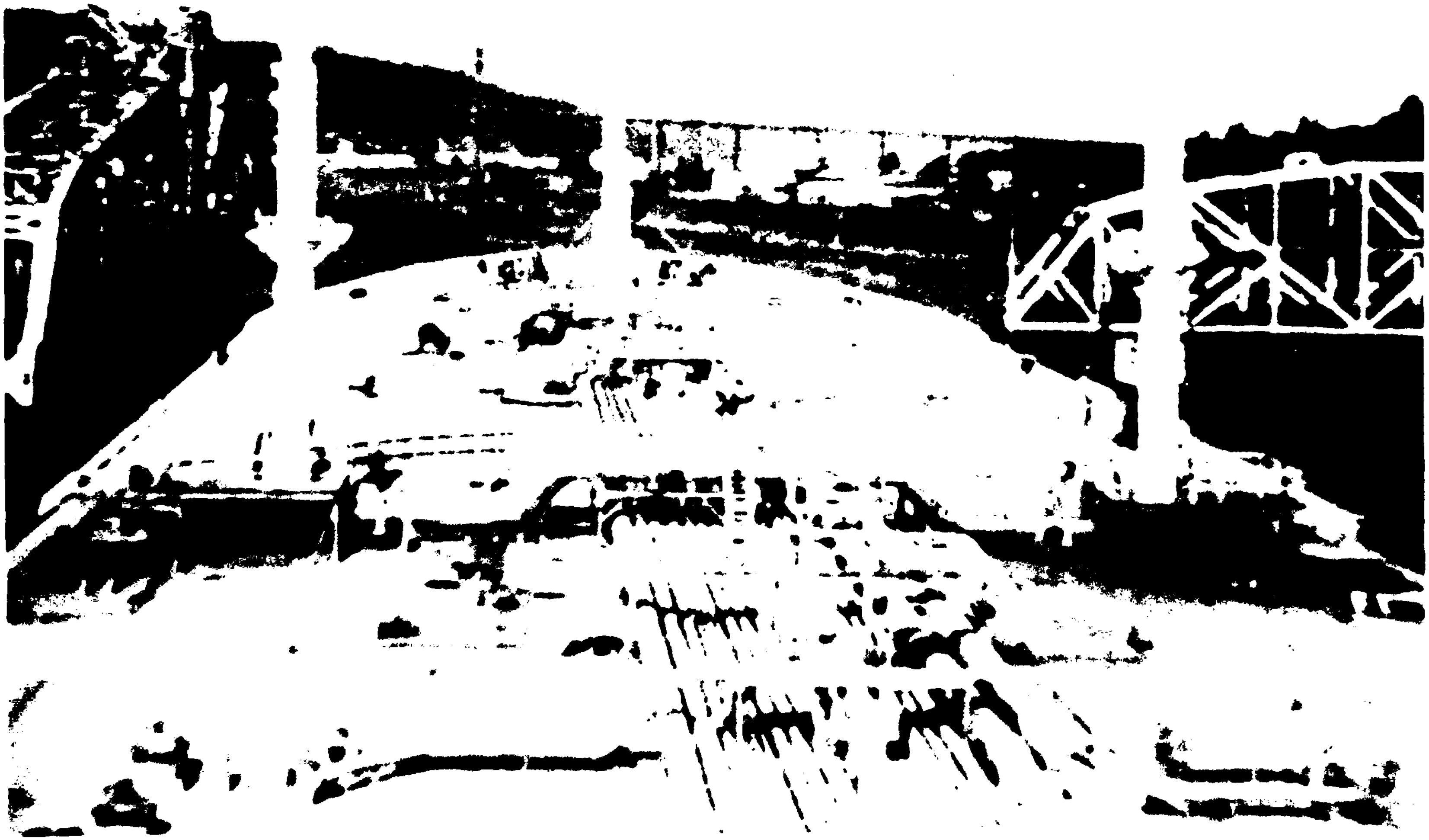
Legislative and Institutional Framework

Legislative and regulatory authority for ships, overwater bridges, and navigational channels is granted to the U.S. Coast Guard, Federal Highway Administration, Federal Railroad Administration, and U.S. Army Corps of Engineers. No agency or unit of government is responsible for the safety of overwater bridges against ship collisions.

A framework has evolved of shared federal and state responsibility for highway bridges, and of shared federal and private responsibility for railroad bridges.

Standards for design and construction are developed in the professional engineering organizations and referenced by regulation. No standards have been developed for the design and construction of bridges to resist ship collisions (with the exception of criteria for fenders to protect railroad bridges), but the framework is an appropriate one for the development of such standards.

Regulatory and institutional activities address parts of the ship-bridge-waterway system: none addresses the functioning of the system as a complex whole. Steps have been taken by the U.S. Coast Guard and U.S. Army Corps of Engineers to involve one another early in deliberations about bridge permits and waterway improvements. Much more interdisciplinary exchange of information and collaborative systems analysis is needed to effect significant improvements in the whole and the parts of this system.



View from the wheelhouse of the 173,000 DWT tanker Atigun Pass (beam, 173 ft) transiting Burlington & Northern Railroad Bridge (swing), horizontal clearance, 230 ft, Portland, Oregon

Photograph: Capt. Mark Michels, Columbia River Pilots Association

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. The problem of ship-bridge collisions is serious.

o While catastrophic collisions are rare, their frequency and severity appear to be increasing. Traditional margins of safety are narrowing as major navigational channels become increasingly obsolescent for the volume of vessel traffic, the greater mass and size of large modern vessels, and the reduced maneuverability of these vessels. Overwater bridges are built without design and construction attention to the interactions of ship, bridge, and waterway, or to the prevention and mitigation of ship collisions.

o Damaging collisions short of bridge collapse are more frequent: several have been near-catastrophic.

o Ship-bridge collisions can easily be envisioned that are far worse than any that have occurred.

o While not within the specific scope of the committee's study, bridges over the inland waterways appear to be at equally serious risk of vessel collisions: tug-barge and push-tow combinations have grown in displacement and are susceptible to forces of the physical environment.

2. Many elements of the ship-bridge-waterway system contribute to the risk of ship collisions with bridges, but the system is not systematically planned or evaluated.

o The fragmentation of jurisdiction and responsibility for the elements of land and marine transportation leaves no single agency or authority to ensure the safety of bridges against ship collisions.

o Coordination has recently been emphasized, but without a structure for effective systems analysis planning and action, it is questionable if adequate coordination will occur.

o Techniques of analysis have been developed to identify threats, hazards, and system vulnerabilities, to estimate risk and evaluate possible consequences, and to project the costs of various accidents as well as those of preventing or mitigating them. A considerable body of literature pertinent to evaluating ship-bridge collision forces has been accumulated but has not been widely disseminated or applied in the United States.

o Similarly, much has been learned about collision-resistant structures and protective systems, but this information has not been sufficiently distributed in the engineering community or uniformly considered in overwater bridge design.

3. Elements of the ship-bridge-waterway system need to be addressed.

o Design criteria for location, design, and protection of overwater bridges against ship collisions have not been developed in the United States.

o Improvements to the major navigational channels and ports and harbors of the United States have not kept pace with the growth of vessel traffic, changes in vessel types, or vessel maneuvering requirements.

o Aids to navigation have not been systematically planned and placed to guide vessel transits under bridges, particularly in areas that offer additional navigational difficulty--for example, bridges located near bends and turns in the channel.

o Motorist warning and restraint systems have been researched and developed but are required only for movable bridges over waterways. Yet, the continuation of traffic following destruction of bridge spans has caused the largest loss of life in ship-bridge collisions.

4. Further research and development are indicated to improve the ship-bridge-waterway system, as well as action on results.

o New systems and onboard aids for precision navigation have been investigated and tried, but information about them has not been effectively distributed, nor has their use been encouraged.

o Marine traffic engineering has been modest and voluntary in the United States. This is adequate for some areas but inadequate for others, particularly those experiencing heavy cross-traffic, mixed use of navigational channels, and vessels carrying hazardous cargoes.

o There are no performance criteria for licenses to pilot or handle vessels in the United States.

o Data for the maneuvering characteristics of vessels in restricted waters are scarce, and there are no maneuvering criteria for vessels in navigational channels or ports and harbors.

o Pilots and other ship handlers need more and better information about the physical environment--wind, tides, currents, water depths, and storms.

Recommendations

1. A national policy needs to be formulated and stated by the U.S. Department of Transportation that new bridges over navigable waterways shall be designed for the possibility of ship collisions and that existing bridges shall be evaluated for protective and mitigative measures.

o The policy should establish coordination between the Federal Highway Administration, U.S. Coast Guard, and Federal Railroad Administration to develop a plan of action directed to these objectives.

o The plan of action needs to consider how funding and regulation can promote collaborative solutions to the problems of new and existing bridges among the several interests involved, including the U.S. Army Corps of Engineers.

2. Engineering criteria need to be developed by the American Association of State Highway and Transportation Officials (AASHTO) and American Railway Engineering Association (AREA)* for consideration of ship collisions in the design of bridges over navigable waters; specifically,

- o Siting and layout;
- o Structural requirements, including redundance and ductility;
- o Geotechnical evaluation and alternatives; and
- o Protective systems.

3. Other necessary criteria should be developed through collaborative and interdisciplinary methods, as the responsibility for acting on them may vary with the type of bridge or owner. Urgently needed are

- o Criteria for motorist warning and restraint systems;
- o Guidelines encouraging the use of threat, risk, and cost evaluations.

4. The U.S. Coast Guard needs to study the navigational problems of vessels transiting overwater bridges and to develop

- o Uniform and site-specific performance criteria for pilots and other vessel handlers;
- o Systems analysis of aids to navigation (and specifications for the aids to be used to mark turns, bends, and bridges);
- o Guidelines for marine traffic engineering; and
- o Criteria for ship maneuverability.

5. Much more interdisciplinary and interagency communication has to be instituted, as well as dissemination of results from research, development, and analysis efforts.

6. The outstanding problems requiring further research and development are

- o Vessel-bridge collisions on inland waterways;
- o Navigational aids and aids to navigation;
- o Ship maneuverability with very small underkeel clearance;

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*AREA has a standard for pier protection systems.

- Methods for assessing the proportion of total ship kinetic energy transferred to a bridge pier in collisions;
- Results of impact forces on ships colliding with fixed objects;
- Training of pilots and other vessel handlers; and
- Multipurpose uses of simulation.

INTRODUCTION

Accidents of ships and bridges* have increased worldwide and in the United States in the past 10 years, tragically emphasized by the loss of 35 lives in the ramming of the Sunshine Skyway Bridge by the Summit Venture on May 9, 1980. Bridges are being proposed or built that are longer and farther seaward, that will carry greater volumes of traffic, and that are at risk of accidents with ships of greater mass and speed.

The loss of life, property damage, and economic consequences of ship collisions with bridges in the past 20 years far exceed those of bridge accidents caused by earthquakes, winds, and waves combined (Saul and Svensson, 1981). Yet, while design criteria have been developed for seismic activity and winds, and are being developed for the challenging environmental conditions faced by new overwater bridges--swift currents, deep water, high waves, and ice--ship collisions have received little design attention (Gerwick, 1983).

Nevertheless, the consequences of ship-bridge collisions have been catastrophic: bridges have been partially destroyed--more than 1300 ft (feet) (400 m [meters]) of the Sunshine Skyway Bridge fell--and cars, trucks, and buses plunged into the water. Traffic has continued unaware or heedless of the destruction: this is, in fact, the cause of the greatest loss of life in collisions of ships with bridges worldwide (Gerwick, 1983). Wreckage has blocked waterways, and bridge connections have remained severed for long periods--all at great economic loss.

While ships have been damaged, the most serious accidents that can be envisioned have not yet occurred--those, for example, of ships carrying hazardous cargoes that may explode or catch fire where populations and industry are concentrated and when bridge traffic is dense.

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*In this report, these accidents are called "collisions of ships and bridges," or "ship-bridge collisions," although the proper term is "allisions," denoting the striking of a fixed object by a moving one, or (as in reports of the U.S. Coast Guard) "ramming."

The Marine Board of the National Research Council has long been concerned about the state of the art of engineering and technology and its application in the marine environment to meet national objectives for the efficient use and protection of the oceans and coasts. In appraising the environmental design criteria appropriate to harsher marine environments, members of the Marine Board became aware of worldwide overwater bridge construction in challenging new locations. One of these, the Storebaelt (Great Belt) Bridge to join the islands of Fyn and Sjaelland in Denmark, was designed and within a day of final contract negotiations for construction when the project was deferred. The piers for this bridge were planned for water depths of 40 m (132 ft) over a navigational channel used by very large crude oil carriers (VLCCs) of 200,000 DWT and more that maintain speeds in the channel of 16 knots to 19 knots for adequate control in the waterway's swift currents. During the design period, two such ships had run aground, more than a kilometer from the navigational channel. Serious consideration was given to preventing catastrophic damage from ship collisions in the design of the bridge.

In its preliminary investigation of the problem of ship-bridge collisions in the United States, the Marine Board found that responsibilities for meeting traffic demands, for public safety, for protection of the marine and coastal environment, for assuring the safety of navigation, and for promoting the growth of commerce are divided among several agencies of the federal government, units of state and local governments, organizations, industries, and individuals. None is singly responsible for preventing or mitigating ship collisions with bridges.

The Marine Board's concern was very much heightened by the Sunshine Skyway Bridge disaster. Acting on its concern, the Marine Board directed the Committee on Ship-Bridge Collisions to review existing knowledge of ship-bridge collisions, the nature and scope of the problem in the United States, pertinent regulatory and institutional considerations, and mitigation strategies. International studies were being undertaken when the committee initiated its study, principally under the aegis of the International Association for Bridge and Structural Engineering (IABSE), an organization that published the first investigation of the subject (Ostenfeld, 1965). Investigations were also being undertaken in foreign countries, and these were consulted. The results of much of this work will be available in the forthcoming proceedings of the IABSE colloquium on ship collisions with bridges and offshore structures (May-June 1983, Copenhagen, Denmark).

The study that is the subject of this report was restricted to bridges in the United States spanning major coastal ports and navigational channels, and to accidental impacts. The waterways of interest were taken to be those carrying large oceangoing ships: a convenient definition proved to be those 30 ft or more in depth. The St. Lawrence Seaway and Great Lakes, as well as most of the inland waterways, were excluded. Also excluded were operational impacts, such as those of ships against the piers of docks and wharves. (It should be understood that exclusion of the 25,000 miles of inland waterways in this country and their several thousand bridges does not indicate lack of concern--some serious accidents are cited as examples in this report that are

outside the committee's geographical scope of inquiry. The charter of the Marine Board at the time the study was undertaken was marine and coastal.)*

The committee's conclusions and recommendations are given in Chapter 2 of this report, immediately following the executive summary and preceding this introduction. Succeeding chapters of the report indicate the bridges within the scope of the study, and briefly recapitulate the historical record of ship-bridge collisions. Two short summary chapters review what is known about the pertinent characteristics of ships and their dynamics in navigational channels and in collision. The chapters following discuss the several elements of prevention or mitigation of such accidents--design of bridges for resistance to ship impacts, geotechnical considerations, and navigational aids. As these would have to be combined systematically for efficiency and safety, a chapter takes up methods that have been used (or that might be used) to estimate the risks of ship collisions, as well as techniques for calculating and comparing the benefits of various mitigation strategies. A brief description is given of the legislative, regulatory, and voluntary standards and programs applicable to bridges over navigational channels.

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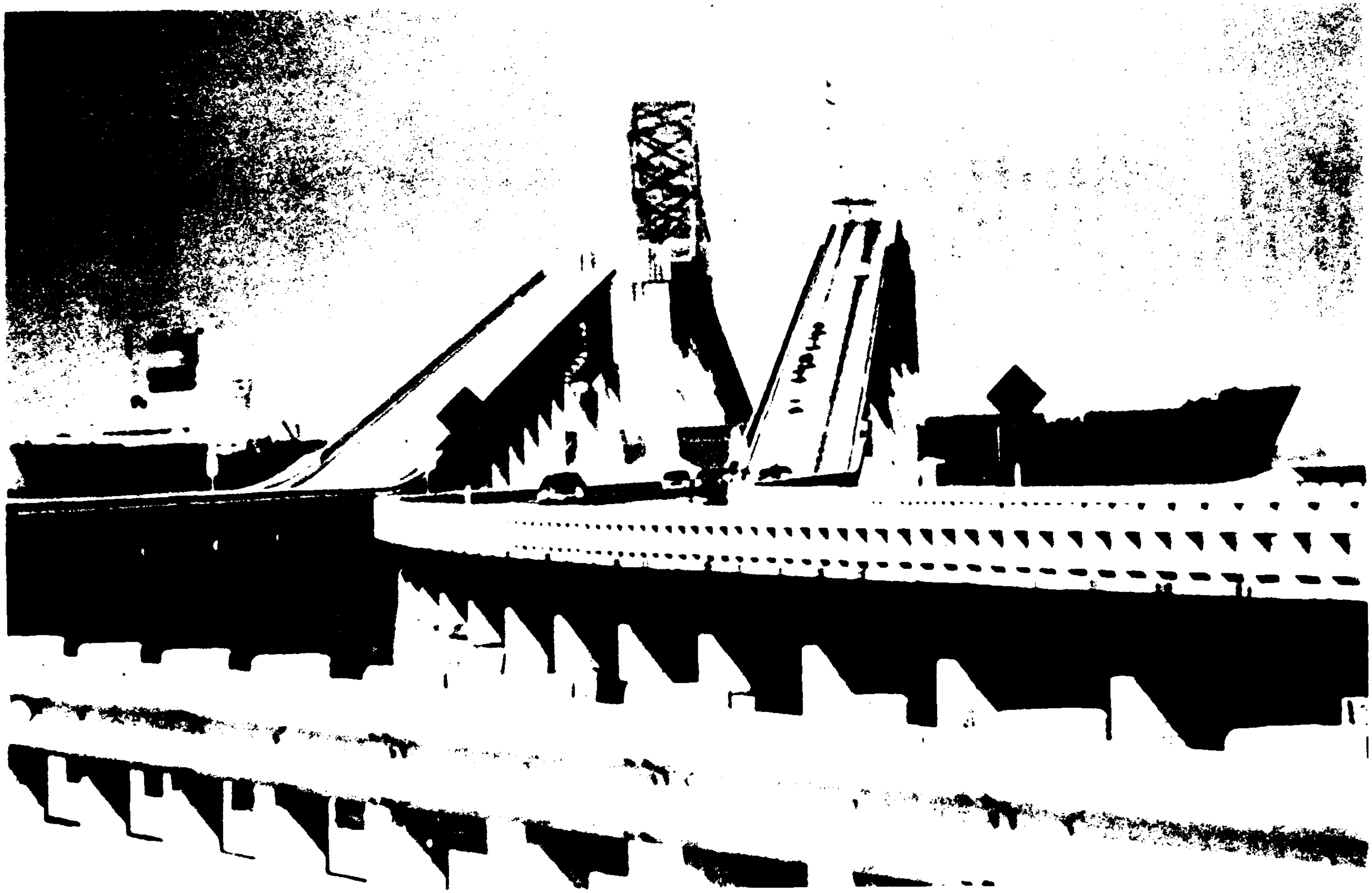
*The Marine Board has since merged with the Maritime Transportation Board of the National Research Council (June 1982). While the new merged unit is denoted the Marine Board, its terms of reference encompass the inland waterways.



Cargo ship transiting Sunshine Skyway Bridge, Florida (foreshortening owing to telephoto lens)

Photograph: Jim Wilt, Florida Department of Transportation

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BRIDGES

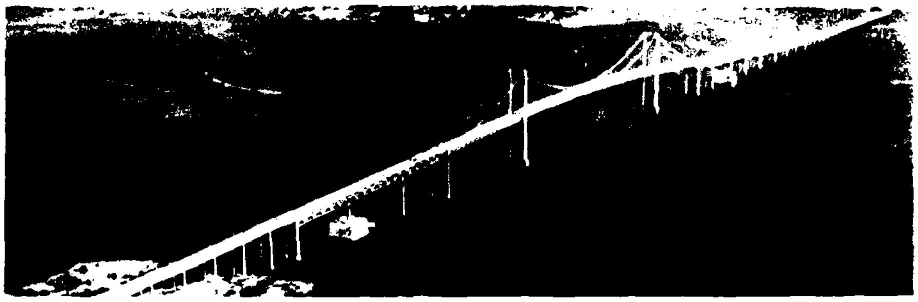
The 133 bridges of interest to the study are listed in the Appendix. These bridges are of two principal types: 79 are fixed and 54 are movable (including bascule, vertical lift, and swing bridges). Highway bridges dominate (102); there are fewer railroad bridges (19) and combined highway and railroad bridges (12). Examples are shown in Figure 1.

Of these bridges spanning major navigational channels or ports, 87 are more than 20 years old; 45 are more than 50 years old. As noted by the General Accounting Office (1981) in a report on bridges in the United States:

> Structural deficiencies occur principally because of lack of proper maintenance due to insufficient funds, exposure to the elements, general wear, and poor initial design. The major reasons for functional obsolescence are increased traffic, changing traffic patterns, and higher safety standards. Many bridges are deficient largely because of advanced age.

Which bridges are critically old, structurally weak, or functionally obsolete may eventually be determined from the not yet completed national inventory of bridges and their condition mandated in 1971 (and described in Chapter 13, "Legislative and Institutional Framework"). The criteria for this inventory do not include the effects of bridges on navigation, but it may readily be surmised that "increased traffic and changing traffic patterns" characterize vessel traffic as well as vehicular traffic and that bridges over navigational channels that are functionally obsolete for vehicular traffic may be functionally obsolete for ship traffic.

Figure 1   Types of bridges spanning waterways



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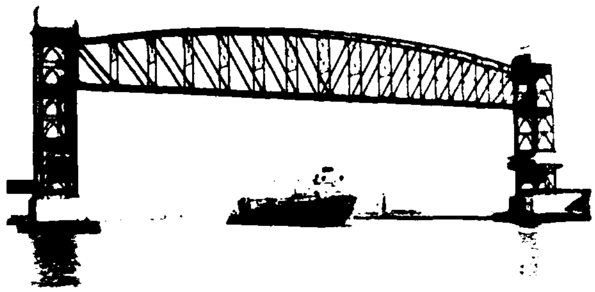

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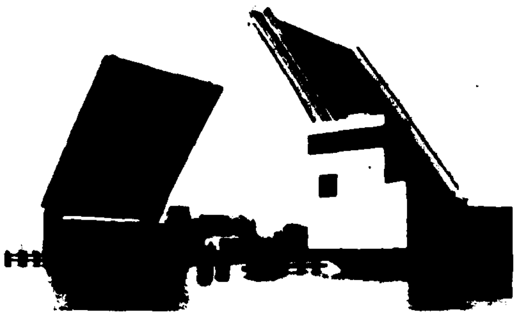

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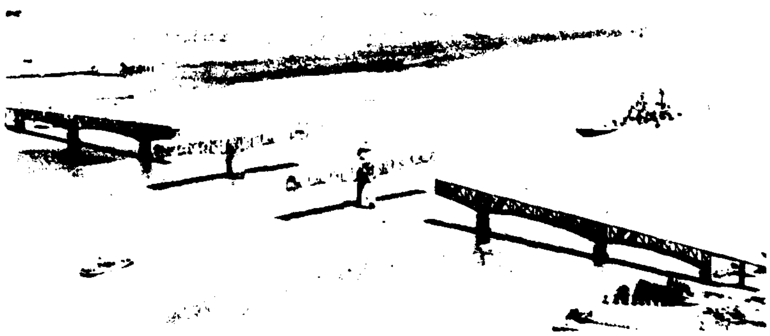

(6)

1 Suspension
(Newport Bridge, Rhode Island)
2 Tied arch
(Fremont Bridge, Oregon)
3 Cantilever truss
(John E. Matthews Bridge, Florida)

4 Vertical lift
(Arthur Kill Railroad Bridge, New Jersey)
5 Bascule
(Third Street Bridge, Delaware)
6 Swing Span
(George P. Coleman Bridge, Virginia)

Photographs: Parsons, Brinckerhoff, Quade & Douglas, Inc.

5

THE HISTORICAL RECORD

Ostenfeld (1965) surveyed ship collisions with bridges (and the Drogden Lighthouse) worldwide and reports available details in 16 case studies. Frandsen (1982) lists 22 "serious" collisions of ships with 18 bridges from 1960 to 1982, worldwide (defining "serious" as collisions entailing interruption of bridge service). Of the 22 serious collisions, 13 were in the United States. The Chesapeake Bay Bridge, Virginia, and the Pontchartrain Bridge, Louisiana, each suffered three such collisions. Of the nine bridges in the United States listed by Frandsen as having been partially destroyed by ship collisions, three are within the scope of this study (the other six span inland waterways).

Frandsen notes the paucity of data and their noncomparability, particularly respecting the costs of such collisions, owing to uncertainties about what is included in calculations of costs, and the changing values of various currencies. The most complete data were gleaned by Frandsen from what he terms "anecdotal" accounts.* These are illuminating, however, about the circumstances of the accidents. The accidents listed by Frandsen for bridges in the United States in the past 20 years are combined with those known to the committee, including some that did not entail interruption of bridge service, in Table 1. Several accidents are to bridges over inland waterways: these are offered to augment general understanding of ship-bridge collisions.

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*A source of information is Engineering News Record, which reports accidents involving bridges not covered by other sources.

TABLE 1 Collisions of vessels and bridges in the United States, 1962-1983

Bridge:	1.	PONTCHARTRAIN BRIDGE, Lake Pontchartrain near New Orleans, Louisiana.
Opening year:		1957; second bridge, 1970.
Bridge struct.:		Prestressed concrete sections on pile bents, 56 ft apart. Vertical clearance 16 ft. Two bascule spans providing 75 ft clearance and 3 fixed humps providing 56 ft by 25 ft openings are the only passages on a length of 24 miles. The bridge was designed to sustain the normal load of b , hitting it, but not a "power collision." The second bridge has a structure similar to that of the first bridge, but spans are increased to 84 ft and 3-pile bents are used instead of 2-pile bents. Increased dimensions of openings for easier vessel passage. To minimize danger to navigation every second bent of the new structure is aligned with every third bent of the old.
Navig. aspects:		The lake is subject to sudden squalls and rough water.
Date/Accident:	1a.	June 16, 1964. Barge tow off course swung in and hit the bridge.
Vessel:		Loaded barges.
Environment:		Normal.
Cause:		Boat operator's negligence. A Coast Guard hearing showed that the captain, who was not at the wheel, was unable to plot a course and to define magnetic north.
Damage:		4 spans collapsed; 6 fatalities.
Remarks:		Estimated cost $125,000; 5 days repair time. The accident happened in spite of the two recently installed radar stations, 88 warning signals, and two-way radio communication.
Other accidents:		Fifth time in 8 years the bridge has been rammed by barges, but the first time with fatalities.
Reference:		Eng. News Rec., June 25, 1964, p. 21.
Date/Accident	1b.	July 1964. Tug hit a pile bent.
Vessel:		Tug towing two barges.
Environment:		Normal.
Cause:		Tug pilot's lack of attention, possibly asleep.
Damage:		Two 56 ft spans fell down; 1 pile bent destroyed.
Remarks:		Bridge hit so many times by barges that repair has become routine. New sections are kept in storage for replacement. Repair time less than 1 week.
Other accidents:		The sixth time the bridge was hit in 8 years and the second within 1 month.
Reference:		Eng. News Rec., July 30, 1964, p. 7.

TABLE 1 (continued)

Date/Accident:	1c.	August, 1974. Tug hit an unprotected pier some way from the navigation span.
Vessel:		Tug pulling 4 empty barges.
Environment:		Normal.
Cause:		The tug pilot had fallen asleep.
Damage:		A 3-span 250 ft section fell down; 2 pile bents demolished; 3 fatalities.
Remarks:		The new bridge was supposed to be more resistant to collisions, "since one pile can be knocked out of a bent without collapsing spans." The ninth time the bridge was hit, killing a total of 9.
Other accidents:		In 1969, a barge crane struck and damaged two 84 ft spans of the second 24 mile causeway, while it was under construction.
References:		Eng. News Rec., April 18, 1968, p. 38-41; Eng. News Rec., February 27, 1969, p. 7; Eng. News Rec., August 8, 1974, p. 20.
Bridge:	2.	CHESAPEAKE BAY BRIDGE AND TUNNEL, Chesapeake Bay, Virginia.
Opening year:		1965.
Bridge struct.:		Actual part of CBBT concrete trestle 3 miles long. Prefabricated 75 ft spans on pile bents, vertical clearance 24 ft. The 17.5 mile CBBT crossing consists of 6 concrete trestle bridges, 2 tunnels, and 2 steel bridges. The tunnel sections provide navigation channels of 1700 ft and 2300 ft widths.
Navig. aspects:		Open ocean.
Date/Accident:	2a.	December 1967. Barge was thrown repeatedly against bridge deck.
Vessel:		Drifting, crewless coal barge.
Environment:		Storm.
Cause:		Barge torn loose from its moorings by the storm.
Damage:		1 span moved 4 ft out of line; 5 others seriously damaged.
Remarks:		Cost $1.3 million (including lost revenue); repair time 15 days.
Reference:		Eng. News Rec., December 14, 1967, p. 27.
Date/Accident:	2b.	January 21, 1972. Ship was thrown repeatedly against bridge deck.
Vessel:		USS *Yancey*, Navy cargo ship, approx. 10,000 DWT.
Environment:		Storm.
Cause:		Ship was torn loose from its moorings by the storm.
Damage:		15 piles supporting five 75 ft spans broke off; 11 other spans were seriously damaged.
Remarks:		Cost $2 million in repairs and $600,000 in revenues lost during 42 days shutdown.
References:		Eng. News Rec., January 29, 1970, p. 17; Eng. News Rec., March 12, 1970, p. 9.

TABLE 1 (continued)

Date/Accident:	2c.	September 21, 1972. Barge was thrown repeatedly against the bridge deck.
Vessel:		The tug Carolyn and Weeks Barge 254.
Environment:		Heavy wind.
Cause:		Broken towline to tug.
Damage:		2 spans fell partly down, five 75 ft sections damaged.
Remarks:		Repair time approx. 1 month; cost $1.1 million in repairs, $0.8 million in lost revenue.
Other accidents:		Rammed for the fifth time in 7 years. Third time the bridge was closed down for repairs.
References:		Eng. New Rec., September 28, 1972, p. 22; Eng. News Rec., November 23, 1972, p. 564; U.S. Coast Guard Casualty Report, "Collision of the Tug 'Carolyn' and 'Weeks Barge 254' with Chesapeake Bay Bridge Tunnel...," NTIS-AD 774-372, Washington, D.C.
Bridge:	3.	SIDNEY LANIER BRIDGE, Brunswick River, Georgia.
Opening year:		1957.
Bridge struct.:		4-lane bridge. Channel span is a 250 ft, steel truss vertical-lift span. The approaches are fixed spans consisting of 3-span continuous units of 150 ft steel girder spans. Vertical clearance in lift span 139 ft/24 ft, in fixed spans 45 ft.
Navig. aspects:		River, 1250 yards wide; bend in channel near bridge.
Date/Accident:		November 7, 1972. Ship hit the bridge next to the lift span.
Vessel:		SS African Neptune, 12,900 DWT freighter.
Environment:		Normal.
Cause:		The helmsman misunderstood the pilot's instructions.
Damage:		A 3-span section fell down; 10 fatalities.
Remarks:		Cost $1.3 million, repair time 6 months. National Transportation Safety Board recommends a study of the hazards of lift-span bridges with narrow openings, deepwater supports, and curved channels.
References:		Eng. News Rec., November 16, 1972, p. 19; Eng. News Rec., August 1, 1974, p. 11. National Transportation Safety Board and U.S. Coast Guard, "SS African Neptune: Collision with the Sidney Lanier Bridge...," NTIS AD-781 298, Washington, D.C.
Bridge:	4.	PASS MANCHAC BRIDGE, Channel between Lake Pontchartrain and Lake Maurepas, Louisiana.
Opening year:		1931.
Bridge struct.:		2-lane bridge, concrete slab on steel girders supported by pile bents. Total length 3012 ft, 51 spans, vertical clearance 50 ft.
Navig. aspects:		--

TABLE 1 (continued)

Date/Accident:		September 1976. Barge hit a pile bent, with 4 prestressed piles.
Vessel:		Barge towed by a tug.
Environment:		Strong currents.
Cause:		The barge off course (tug pilot held responsible).
Damage:		Pile bent destroyed; 3 spans (80 ft, 107.5 ft, and 70 ft) fell down; at least 1 fatality.
Remarks:		Repair time 4-6 months.
Other accidents:		--
Reference:		Eng. News Rec., September 23, 1976, p. 41.
Bridge:	5.	BENJAMIN HARRISON MEMORIAL BRIDGE, James River, Virginia.
Opening year:		1967.
Bridge struct.:		2-lane bridge with vertical-lift span, 363 ft long, and tower spans, 241 ft long, in steel truss. Adjacent spans in prestressed concrete. Total length 4463 ft. Clearance under tower spans 30 ft.
Navig. aspects:		River with dredged channel 300 ft wide and 34 ft deep. Bends in channel upstream and downstream; low current velocity.
Date/Accident:		February 24, 1977. Ship hit and destroyed the pier between tower span and adjacent span, after which the ship's hull passed under the tower span and the deck house hit the steel truss.
Vessel:		SS Marine Floridian, 25,000 DWT tanker in ballast
Environment:		Normal.
Cause:		Electrical fault in steering gear.
Damage:		The northern tower span and its associated equipment were demolished. Support pier between tower span and approach causeway was destroyed. One section of causeway fell down. Center span and lift mechanism were damaged extensively and subsequently collapsed during efforts to salvage them. Cost of rebuilding estimated at $7,000,000. Repair time approx. 2 years.
Remarks:		National Transportation Safety Board recommends warning signals and traffic control devices in accordance with guidelines of Federal Highway Administration.
Other accidents:		--
References:		Eng. News Rec., March 3, 1977, p. 11; Eng. News Rec., March 17, 1977, p. 16; National Transportation Safety Board (1978) "US Tankship SS Marine Floridian, Collision with Benjamin Harrison Memorial Bridge," NTIS PB-293 237, Washington, D.C.

TABLE 1 (continued)

Bridge:	6.	UNION AVENUE BRIDGE, Passaic River, New Jersey.
Opening year:		1897.
Bridge struct.:		Two-lane bridge with swing span; stone block pier on timber piles.
Navig. aspects:		--
Date/Accident:		April 1977. Barge hit pier at the navigation span.
Vessel:		Empty oil barge towed by tug.
Environment:		Normal.
Cause:		Broken towline to tug.
Damage:		Pier and 1 end of 54 ft long side span fell into the river.
Remarks:		Repair time 5-6 months. Damaged pier rebuilt in reinforced concrete; cost estimate $600,000.
Other accidents:		--
Reference:		Eng. News Rec., August 5, 1977, p. 10.

Bridge:	7.	SOUTHERN PACIFIC RAILROAD BRIDGE, Atchafalaya River near Berwick, Louisiana.
Opening year:		1907. Rebuilt 1971: lift span replacing swing span.
Bridge struct.:		Steel truss, 320 ft lift span. Vertical clearance 73 ft in open position. Pier protected by fenders.
Navig. aspects:		Bend in channel in approach to bridge. Strong currents during high water make the downbound passage hazardous for many towing operations. Two other bridges in the immediate vicinity.
Date/Accident:		April 1, 1978. The lead barge hit the bridge superstructure in the side span of the railroad bridge, after having hit a bridge pier of the nearby highway bridge.
Vessel:		Towboat pushing 4 barges.
Environment:		High water with strong tidal currents; crosscurrents of 2-5 knots common in this location.
Cause:		Careless navigation (underpowered tow).
Damage:		One 232 ft long steel truss span tumbled off the supporting piers and sank. Damage totalled $1.4 million, including costs of rerouting rail traffic.
Remarks:		--
Other accidents:		The bridge was struck by vessels 534 times between 1946 and 1978.
References:		National Transportation Safety Board (1980), "Collision of M/V "STUD" with the Southern Pacific Railroad Bridge...," Marine Accident Report, NTSB-MAR-80-5, Washington, D.C.; R. B. Dayton (1976), Analysis of Bridge Collision Incidents, Vol. I, CG-D-77-76 (Washington, D.C.: U.S. Coast Guard).

TABLE 1 (continued)

Bridge:	8.	SUNSHINE SKYWAY BRIDGE, Tampa Bay, Florida.
Opening year:		Eastern bridge 1954; western bridge 1971.
Bridge struct.:		2 identical bridges, separated 120 ft. Total length 22,424 ft, mainly concrete trestle spans. Central part: 3-span 1584 ft steel cantilever through truss, with 864 ft main span and 360 ft anchor spans, flanked by 2 steel deck truss spans on each side. Clearance in main span 800 ft by 140 ft. Anchor pier: 2-column reinforced concrete frame on reinforced concrete shaft extending down to bay bottom, founded on prestressed concrete piles.
Navig. aspects:		Ship traffic, about 11,000 passages per year, is concentrated in dredged main channel, 400 ft wide, 43 ft deep. Depths outside channel 25-30 ft. In approach from sea, channel has 18 deg. bend approx. 0.7 nmi (nautical mile) before the bridge.
Date/Accident:		May 9, 1980. Stem of ship hit concrete pier column of anchor pier 800 ft from center of navigational channel.
Vessel:		Summit Venture, 35,000 DWT bulk carrier in ballast.
Environment:		Rough weather with low visibility.
Cause:		Pilot's careless navigation in spite of the weather.
Damage:		Anchor pier destroyed and 1300 ft of 3 steel truss spans fell into the bay. 35 fatalities.
Remarks:		No impact load codes for navigational structures in Florida. Bridge not designed for progressive collapse. NTSB recommends standards for bridge protection systems. Bridge not rebuilt. Cable-stayed bridge under construction to replace two existing bridges.
Other accidents:		At least 10 minor accidents since 1969; 2 major near-accidents in 1980.
References:		Eng. News Rec., May 15, 1980, p. 12; National Transportation Safety Board (1981), "Ramming of the Sunshine Skyway Bridge...," Marine Accident Report, NTSB-Mar-81-3, Washington, D.C.

Bridge:	9.	HANNIBAL-RAILROAD BRIDGE, Mississippi River, Hannibal, Missouri.
Opening year:		1868.
Bridge struct.:		Low-level steel truss with swing span; length 1580 ft.
Navig. aspects:		--
Date/Accident:		May 1982. Towboat struck abutment while passing swing span, barges broke loose, towboat lost control and swung.
Vessel:		Towboat pushing 15 barges.
Environment:		Normal.
Cause:		--
Damage:		1 span fell.
Remarks:		--
Other accidents:		--
Reference:		Eng. News Rec., May 13, 1982, p. 35.

TABLE 1 (continued)

Bridge: 10.	MOUNT HOPE BRIDGE, Mount Hope Bay (Narragansett Bay), Rhode Island.
Opening year:	1927.
Bridge struct.:	Highway bridge, suspension--main span about 700 ft, towers in steel lattice; vertical clearance about 135 ft, horizontal clearance 585 ft.
Navig. aspects:	--
Date/Accident:	1975. Edge of ship sliced 40% through one leg of steel main tower: owing to shape of ship, deck struck tower before hull struck footing.
Vessel:	--
Environment:	Night, heavy fog.
Cause:	Pilot apparently did not hear bridge's warning bell.
Damage:	Pier glanced, damage minor; tower leg close to collapse, but successfully repaired.
Remarks:	Near-catastrophic.
Other accidents:	--
References:	Frandsen and Langso (1980); Committee on Ship-Bridge Collisions.

Bridge: 11.	GEORGE P. COLEMAN BRIDGE, York River, Yorktown, Virginia
Opening year:	1952.
Bridge struct.:	Highway bridge with twin 500 ft swing spans; vertical clearance with spans closed 60 ft, with spans open, unlimited, over 450 ft wide navigational channel.
Navig. aspects:	--
Date/Accident:	December 13, 1975. Navy cruiser was proceeding upstream to fueling station above bridge. Signals having been exchanged between vessel and bridge operator, bridge started to open, but operator perceived vessel's speed would not allow time for bridge superstructure to clear channel. Operator decided to close swing span to give vessel (now "full astern") more room to stop. Vessel drifted into span, pushing it 35° on pivot in wrong direction.
Vessel:	USS *Albany*.
Environment:	--
Cause:	Excessive speed (?)
Damage:	Electrical cables and limit switches torn loose; pinions run off circular rack gear, scraped paint.
Remarks:	Near-catastrophic; slightly greater impact could have caused collapse.
Other accidents:	--
Reference:	Committee on Ship-Bridge Collisions.

TABLE 1 (continued)

Bridge:	12.	WEST SPOKANE STREET BRIDGE, West Waterway Entrance Channel to Duwamish Waterway, Seattle, Washington.
Opening year:		1924, 1930.
Bridge struct.:		Twin highway bascule bridges set at 45° angle to channel; horizontal clearance 150 ft, vertical clearance 53 ft at low water, 42 ft at high water, over channel 200 ft wide.
Navig. aspects:		Cross-channel currents at bridges common; ships moored in channel on both sides of bridges, railroad bridge ahead of highway bridges, also turn into Duwamish Waterway.
Date/Accident:		June 1978. Vessel hit superstructure of north bascule span before bridge opened.
Vessel:		--
Environment:		--
Cause:		--
Damage:		Span inoperable; bridge dismantled.
Remarks:		Difficult to judge center of bridge, owing to angle of crossing.
Other accidents:		Bridges struck several times; 7 accidents in vicinity since 1972, some involving protective fendering of railroad bridge, some moored vessels.
Reference:		U.S. Army Corps of Engineers, Seattle.

Bridge:	13.	NEWPORT BRIDGE, Eastern Passage, Narragansett Bay, Newport, Rhode Island.
Opening year:		1969.
Bridge struct.:		Highway bridge, 2 miles long; central 3-span suspension bridge; main piers caisson-type, founded on steel piles driven into glacial sands; main span 1600 ft; horizontal clearance 1500 ft, vertical clearance 215 ft.
Navig. aspects:		Minimum water depth under main span 90 ft.
Date/Accident:		February 19, 1981. Fully laden tanker struck main tower pier head on at estimated speed of 6 knots.
Vessel:		Gerd Maersk, 18,700 DWT.
Environment:		Dense fog.
Cause:		Pilot could not determine pier location in fog.
Damage:		Ship shortened 11 ft by bow crushing against massive pier; ship came to complete stop and drifted off pier. No damage to bridge other than scraping on pier cap block.
Remarks:		--
Other accidents:		--
Reference:		Committee on Ship-Bridge Collisions.

TABLE 1 (continued)

Bridge:	14.	FRANCIS SCOTT KEY BRIDGE, Outer Baltimore Harbor Crossing, Maryland.
Opening year:		1972.
Bridge struct.:		Fixed highway bridge, 4 main support columns with concrete camel pier protection devices, fendered with timber.
Navig. aspects:		Vertical clearance 185 ft, horizontal clearance 1100 ft.
Date/Accident:		August 29, 1980. Vessel sailing at 12 knots lost all propulsion and control about 600 yards from bridge. Vessel drifted into main pier at speed of about 6 knots.
Vessel:		Blue Nagoya (Ro-Ro/containership).
Environment:		Haze; visibility 2 miles.
Cause:		Shorting of main electrical control board; total loss of power and control.
Damage:		Protective concrete structure destroyed.
Remarks:		--
Other accidents:		--
Reference:		U.S.Coast Guard accident investigation report, 9 December 1980.

Bridge	15.	SAN FRANCISCO-OAKLAND BAY BRIDGE, California.
Opening year:		1932.
Bridge struct.:		Fixed highway bridge: truss and cantilever section from Oakland to Yerba Buena Island, double suspension span to San Francisco.
Navig. aspects:		178-183 ft vertical clearance in the affected span at mean high water; 2224 ft horizontal clearance.
Date/Accident:		September 1977. Bridge superstructure struck by crane mounted on barge.
Vessel:		Tug Columbia towing barge-mounted crane.
Environment:		Clear.
Cause:		Failure to note height of crane.
Damage:		Lower chord member of cantilever truss damaged; had to be replaced (about 50% impaired)
Remarks:		--
Other accidents:		Cargo ship Brilliant Star struck timber fender system on anchor pier D (February 22, 1980); about $300,000 damage to protective system only.
References:		U.S. Coast Guard District 12; California Department of Transportation District 4.

Bridge:	16.	RICHMOND-SAN RAFAEL BRIDGE, California
Opening year:		1951.
Bridge struct.:		Fixed highway bridge, cantilever truss; bell-shaped bridge piers protected by fender systems.

TABLE 1 (continued)

Navig. aspects:	Two navigational openings; for main channel, 1000 ft horizontal clearance, 185 ft vertical clearance (above mean high water); for East Channel, 465 ft horizontal clearance, 118 ft vertical clearance.
Date/Accident:	April 12, 1979. Gasoline-loaded barge under tow struck timber fender system.
Vessel:	Tug Sea Wolf and gasoline barge.
Environment:	Night (4:30 a.m.), clear.
Cause:	--
Damage:	40,000 gallons of gasoline spilled; 1/2 to 3/4 of timbers destroyed. Replaced with heavier concrete and steel system at cost of $1.5 million.
Remarks:	Timber fender system was equipped with automatic sprinkler system (though subject to frequent marine fouling); no fire or explosion occurred in this accident.
Other accidents:	Damage to protective systems from vessels about once yearly.
References:	U.S. Coast Guard District 12; California Department of Transportation District 4.

Bridge: 17.	PENN CENTRAL TRANSPORATION CO. BRIDGE, Chesapeake and Delaware Canal, Delaware.
Opening year:	1927.
Bridge struct.:	Vertical lift railroad bridge; vertical clearance 45 ft closed, 133 ft open (at lower mean high water); horizontal clearance 522 ft.
Navig. aspects:	2-3 knots following current.
Date/Accident:	February 1, 1973. General cargo ship proceeding up canal at about 12 knots noticed span closed about 1/4 mile from bridge: collision inevitable. Ship struck lift span just 60 s after passage of train.
Vessel:	SS Yorkmar.
Environment:	Dense fog.
Cause:	Immoderate speed, failure to signal bridge, inadequate communications between canal dispatcher and bridge operator.
Damage:	Extensive damage to bridge and ship; 1 fatality.
Remarks:	Improved procedures instituted on canal for passing under bridges.
Other accidents:	--
Reference:	U.S. Coast Guard, Proc. Marine Safety Council, September 1973, pp. 183-187.

TABLE 1 (continued)

Bridge: 18.	OUTERBRIDGE CROSSING, Kill Van Kull and Arthur Kill, Perth Amboy, New Jersey and Staten Island, New York.
Opening year:	1928
Bridge struct.:	Fixed highway bridge; horizontal clearance 675 ft, vertical clearance 143 ft at lower water; piers protected by cofferdam cells.
Navig. aspects:	Main pier on New York side outside turn in channel for northbound vessels.
Date/Accident:	October 13, 1979. Tanker approaching bridge went wide on turn, collided head on with center protective cell. Cofferdam structure burst open, spilling sand; piling hit by ship pulled out, remainder bent over at river bottom.
Vessel:	45,000 DWT tanker.
Environment:	Heavy fog.
Cause:	--
Damage:	Damage to ship minimal; bridge pier not touched; sacrificial cell destroyed.
Remarks:	Protective system performed as intended: total cost of protective system installed in 1968 for two bridges $1 million.
Other accidents:	Bridge struck by small tanker in 1960, demolishing former timber fendering and ripping ship hull; tanker collision in 1963 damaged ship hull.
Reference:	Civil Engineering-ASCE, February 1982, pp. 67-68.

Bridge: 19.	EAST 11th STREET BRIDGE, BLAIR WATERWAY, Tacoma, Washington.
Opening year:	1953.
Bridge struct.:	4-lane highway bascule bridge.
Navig. aspects:	Horizontal clearance 150 ft.
Date/Accident:	March 1983. Ship struck leaf of bridge that was about 3/4 open.
Vessel:	Ro-Ro cargo ship Dilkara, 653 ft long, 31.5 ft draft.
Environment:	Normal.
Cause:	Electrical or mechanical failure halted opening of bridge.
Damage:	Outer 20 ft of leaf destroyed, girders bent; bridge traffic rerouted.
Other accidents:	Bridge struck 29 times since 1978; previously struck by the same ship in 1976, bridge closed 11 days, $178,000 for repairs.
Reference:	Eng. News Rec., April 7, 1983.

Bridge: 20.	EUGENE TALMADGE MEMORIAL BRIDGE, Savannah River, Savannah, Georgia.
Opening year:	1954.
Bridge struct.:	Fixed highway bridge, 3-span cantilever truss.

TABLE 1 (continued)

Navig. aspects:	Horizontal clearance 600 ft over 400 ft channel; vertical clearance 136 ft at high water.
Date/Accident:	July 25, 1983. Ship with 131 ft mast passed under bridge, but cargo boom (140 ft height) had been mounted on deck. Boom ripped out both bottom chord members of suspended truss span and buckled deck. Before traffic could be halted, a tractor-trailor truck and bus crossed damaged section without incident. Bridge survived collision by cantilevering from erection pins that had been left in place.
Vessel:	Cargo ship, 694 ft length.
Environment:	Clear, 7:20 a.m.
Cause:	Inattention to height of crane boom.
Damage:	Bridge closed to highway traffic for several months. Cost of repairs $500,000. Ship damage limited to crane boom. No injuries.
Remarks:	Shipping interests have objected to restricted vertical clearance for several years.
Other accidents:	--
Reference:	Committee on Ship-Bridge Collisions.

Figure 2 shows the distribution of collisions by age of the bridge; interestingly, many bridges are struck when relatively new. While this distribution invites speculation about causes and probabilities of ship-bridge collisions, the complexity of causality in such events (as indicated in succeeding sections) warns against it. The number of other accidents cited in Table 1--for example, 534 vessel strikes against the railroad bridge in Berwick, Louisiana, between 1946 and 1978--warns against drawing the conclusion that bridges are immune from "serious" ship collisions at any age.

Frandsen notes that the annual occurrence of serious ship-bridge collisions worldwide increased from 0.5 for the period 1960-1970 to 1.5 for the period 1971-1982 but cautions that as such serious collisions are rare, the statistical base is small.

The statistical base is also more anecdotal than complete but is nevertheless sufficient to indicate that the damages, economic effects, and, most importantly, the loss of more than 100 lives (56 in the United States) from ship collisions with bridges far exceed those from earthquakes, winds, and waves (Saul and Svensson, 1981). Yet, design standards for bridges over waterways address earthquake and wind forces and remain silent about ship impacts.

The record of ship-bridge collisions reveals some preliminary considerations for design that would not normally occur to a bridge engineer. Table 2, for example, indicates that in 19 ship-bridge collisions worldwide that were subsequently investigated, 13 bridges were struck in approach piers and only 6 in the main piers (Saul and Svensson, 1982a). In three of the collisions with approach piers, the side superstructure of the bridge was also struck. Of the accidents to bridges in the United States, 4 were with piers other than the main piers, or outside the navigational channel, and 9 involved the bridge superstructure. Tall masts or crane booms struck the bridge superstructure in three of the accidents listed in Table 1, and in Singapore, the derrick of a drill ship recently severed the cables of an aerial tramway, killing 7 people, and injuring 13.

Four of the bridges in the United States that have been struck repeatedly--and at least once seriously--by vessels are located near bends or turns in navigational channels, and one is skewed 45° relative to the channel. An analysis by the U.S. Coast Guard (1980) of its casualty data for 1979 indicated that the majority of accidents occurred within one mile of a bridge: of these, most were also near or in a bend or turn of the channel. Many were rammings of bridge piers.

This suggests that bridges over waterways may create or aggravate difficult areas of navigation.* The accidents listed in Table 1

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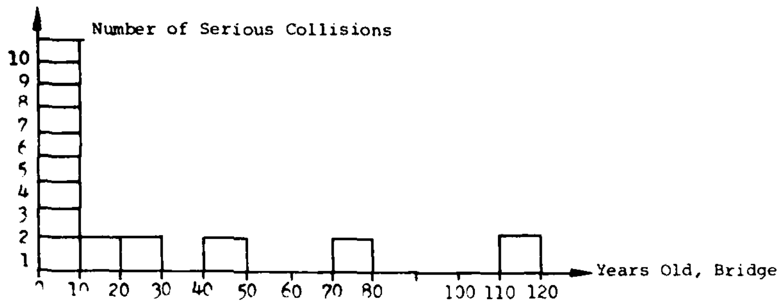
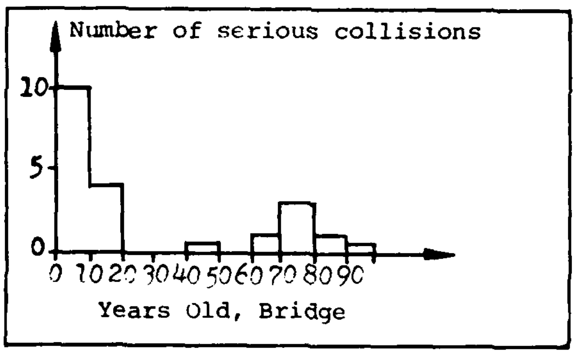
*The historical record for the United States also suggests particular problems of tugboats, towboats, and barges on the inland waterways.

Figure 2 Number of serious ship-bridge collisions* in relation to age of bridge



(a) In the United States, 1971-1983**



(b) Worldwide, 1971-1982***

*Entailing interruption of bridge connection
**SOURCE: A. G. Frandsen (1982), "Accidents Involving Bridges," <u>IABSE Colloquium, Introductory Report</u>, p. 14.
***SOURCE: Committee on Ship-Bridge Collisions.

also suggest that bridge protective systems can reduce or prevent catastrophic impacts.*

Succeeding chapters of this report follow these suggested lines of inquiry and describe in detail the considerations important to the assessment and mitigation of ship-bridge impacts in the bridge-ship-waterway system.

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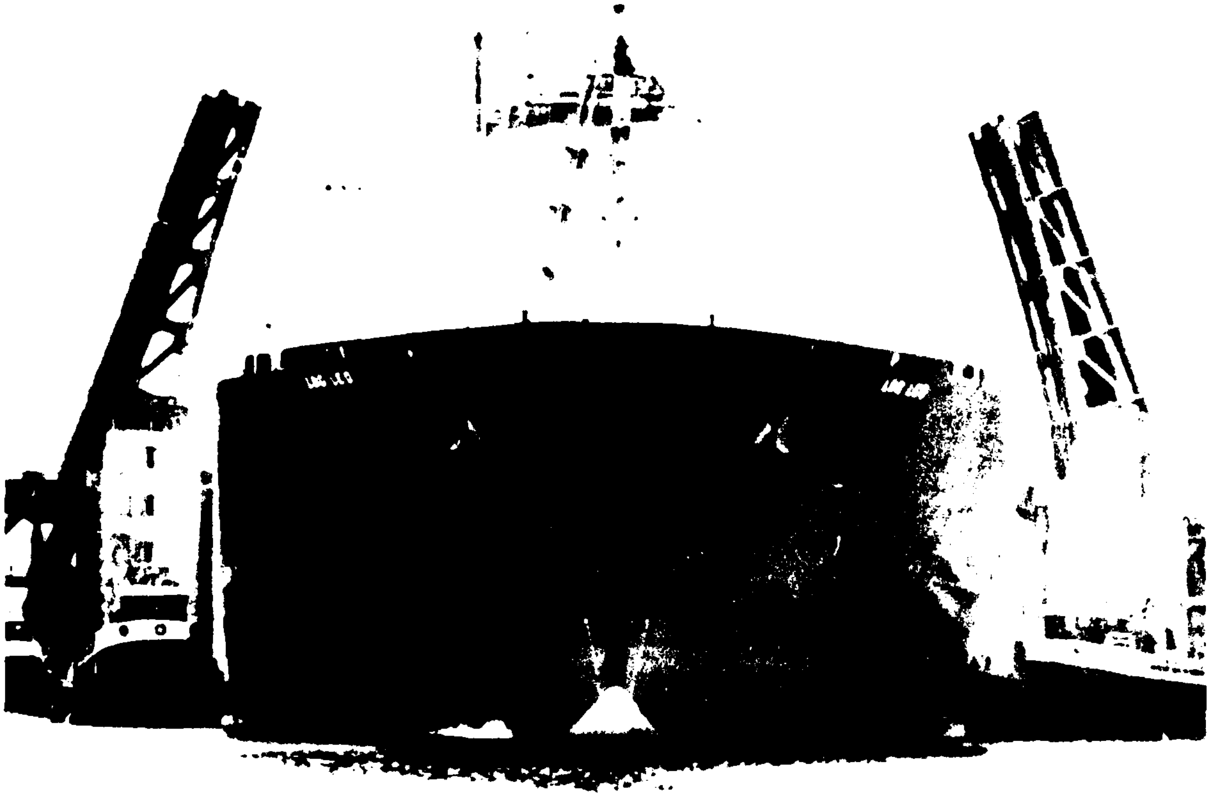
*It should be noted that movable bridges are more sensitive than fixed bridges to small impacts. Permanent deflections (even if they are not large) can damage the moving parts. Considerable costs, as well as delayed resumption of traffic, may be incurred.

Table 2 Ship-bridge collisions (worldwide) by location of impact*

Bridge	Country	Year	Main pier	Side pier
Severn Railway	England	1960		X
Richmond-SanRafael	USA	1961	X	
Outerbridge	USA	1963	X	
Sorsund	Norway	1963		X
Maracaibo	Venezuela	1964		X
Chesapeake Bay	USA	1970		X
Chesapeake Bay	USA	1972		X
Sidney Lanier	USA	1972		X*
Mount Hope	USA	1975	X	
Tasman	Australia	1975		X
Fraser River	Canada	1975		X
Grand Narrows, CNR	Canada	1975	X	
Chesapeake Bay	USA	1976		X
Pass Manchac	USA	1976		X
Benj.Harrison Memor.	USA	1977		X*
Union Avenue	USA	1977	X	
Burrard Inlet, CNR	Canada	1979		X*
Sunshine Skyway	USA	1980		X
Newport Bridge	USA	1981	X	
		19	6	13

* superstructure of side span hit

*SOURCE: R. Saul and H. Svensson (1982), "Means of Reducing the Consequences of Ship Collisions with Bridges and Offshore Structures," IABSE Colloquium, Introductory Report, p. 177.



<u>LNG Leo</u> (liquefied natural gas carrier) transiting Fore River Bridge, Quincy, Massachusetts

Photograph: Richard W. Green, <u>Patriot Ledger</u>

6

CONSIDERATIONS OF SHIPS AND WATERWAYS

New overwater bridges are likely to be longer, nearer the sea, and built to carry more traffic than older bridges. Their piers are apt to be located well out in the waterway, close to the channel lines. Partly because of their location, these bridges are at higher risk of collision with ships of great mass and speed. The press of economy (particularly in fuel consumption) and the very small proportion of ship travel time spent in port calls, relative to time spent on the open ocean, have produced a variety of ships whose principal design consideration is not maneuverability in ports and navigational channels.

Moreover, the design and improvement of the navigational channels in major coastal ports of the United States have not kept pace with changes in the nature and characteristics of the world merchant fleet, or with increasing volumes of traffic (Marine Board, 1983). The siting and design of bridges may aggravate or mitigate these factors.

As ship-bridge collisions involve ship, waterway, and bridge, the salient characteristics of ships and waterways will be discussed briefly in this chapter.

Ships

A number of distinct types of ships have evolved in recent years to perform specific functions or to serve classes of trade (profiles are shown in Figure 3). Despite important differences, some general rules of thumb can be described for the purposes of this analysis.

The ships that are of greatest interest are those that can cause the greatest damage. Generally, these are the largest that can pass through the navigational channel under the bridge. The sizes and shapes of ships have changed dramatically in the last 20 years. Tankers have grown enormously and are often 10 times larger than tankers of the last generation. Containerships now carry most of the trade formerly carried by smaller break-bulk ships, and because they can carry so many containers on deck, they will have less vertical clearance under a bridge. Figure 4 illustrates the relationship of size between a typical containership and a proposed replacement of the Sunshine Skyway Bridge.

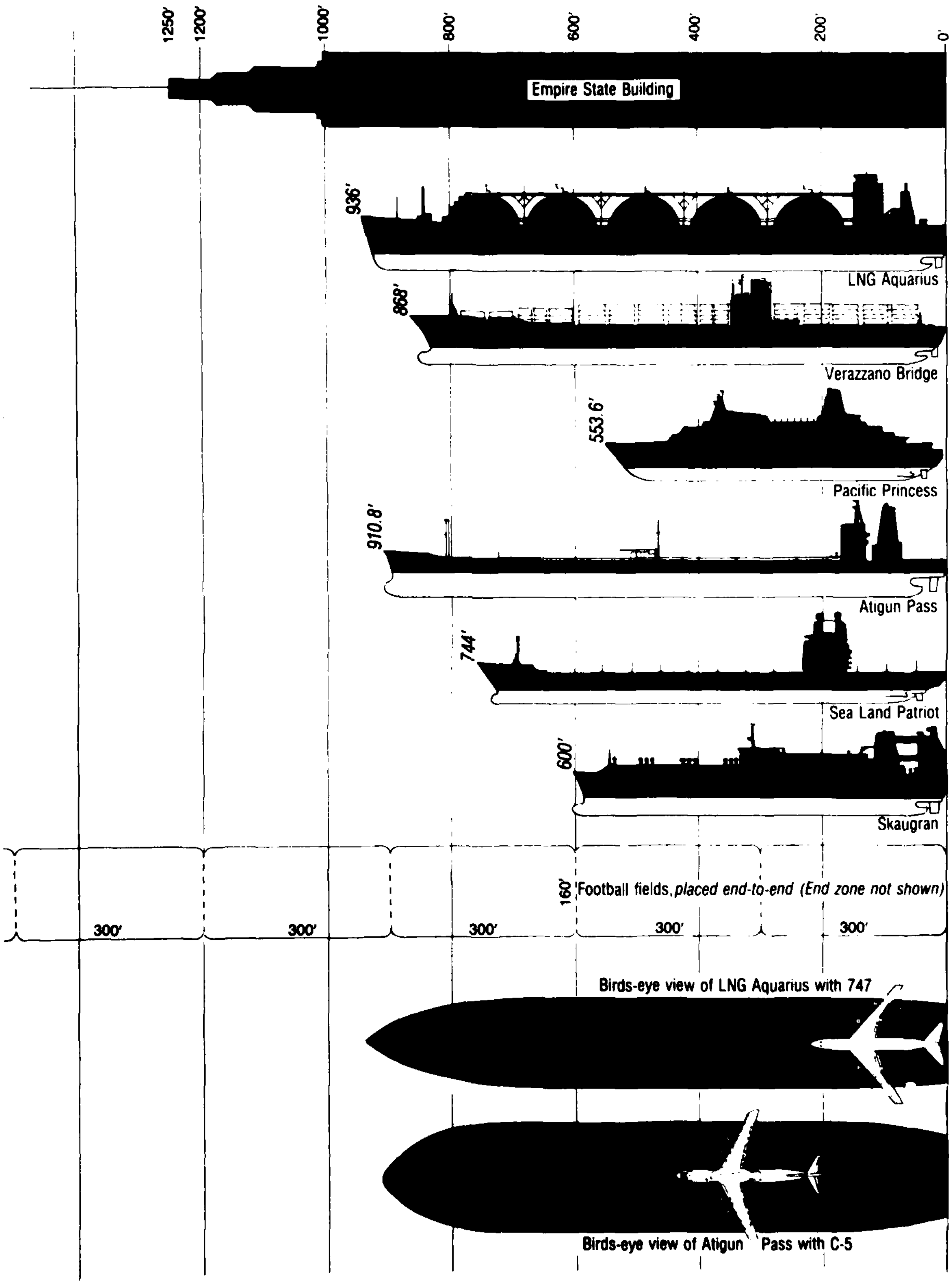


Figure 3 Comparisons of size and profile, typical ships calling on ports of the United States

Collision Impact

The impact force of a ship in a collision with a bridge will depend on the kinetic energy transmitted to the bridge by the ship and the time over which the energy is transmitted. The available kinetic energy of a ship is given by

$$KE = \frac{1}{2} M \times V^2$$

where M is the mass of the ship and the water entrained around it (collectively referred to as the virtual mass of the ship), and V is the speed of the ship. The virtual mass of typical ship forms is usually only slightly larger than the ship's own mass. The difference between the mass and the virtual mass is called the added mass and is typically 5 percent to 10 percent of the ship's mass for motion in the forward direction (DeBord, 1983).

Although there is no ambiguity in the term "mass of the ship," it should be understood that this is not a commonly used description of ship size. The most popular measure, gross registered tonnage (GRT), and all other measures of "tonnage," refer to the volume of the ship, and are intended to indicate the ship's cargo-carrying ability. Another popular measure of ship size is deadweight tonnage (DWT), which refers to the weight of cargo, fuel, and other expendables the ship can carry. The deadweight capacity of a containership can be less than half the ship's total weight. Thus, it is best to use only the ship's displacement in computing its mass.

The other factor in the available kinetic energy of a ship is its speed at time of impact. Most modern ships are capable of speeds in excess of 15 knots at sea. With this reserve horsepower, the speeds of ships in constrained waterways will be limited by the judgment of pilots or ship masters, or by local rules and regulations. Nevertheless, many ships must preserve a minimum speed to maintain headway and to counteract the effects of currents and wind. Ships with direct-connected diesel engines have a minimum operating speed (often between 6 and 8 knots) and may only be able to reverse engines a limited number of times.

Estimating the Kinetic Energy at Impact

To compute the impact of a ship against a bridge, the available kinetic energy must be computed. The difficulty in making the computation is that a variety of ships may pass under the bridge. Those passing under bridges today differ dramatically from those of 30 years ago, and very likely from those of 30 years in the future. Since bridge structures are designed for lifetimes that greatly exceed the turnover of the world fleet, it seems sensible to estimate the impact kinetic energy on some basis other than that of existing traffic patterns under the bridge. It may be noted that if the navigational channel under consideration is at least 300 ft wide and 30 ft deep, virtually any

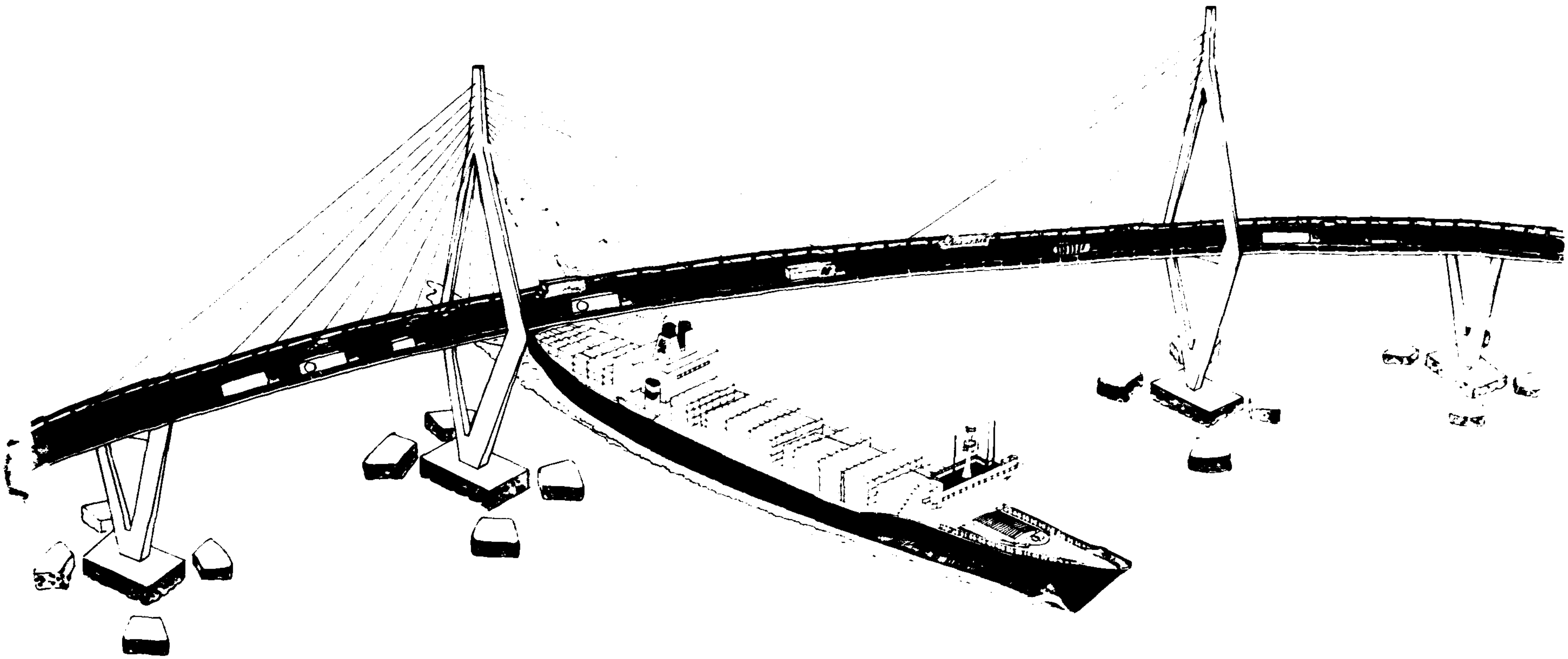


Figure 4 Size relationships of ship and bridge--a relatively long main span (1200 ft) and modest-size containership (719 ft length, 95 ft beam, 34 ft draft)

existing ship in the world can pass through it. The largest supertankers, of course, would be almost entirely empty and unlikely to be plying the waterway for economic reasons, but a large containership might be half-full, as is common in many ports of the United States. Large coal colliers are now partially loaded at terminals in port and "topped off" by barges offshore or at foreign ports. Experience also indicates that whatever the channel depth, ships with drafts very nearly equal to that depth will eventually ply the waterway (Marine Board, 1983).

The beam of typical ship forms varies between 10 percent of the length for high-speed ships to somewhat less than 20 percent for the widest tankers. This relationship results from several factors, principally roll stability. The maximum length of a ship that can ply the waterway in question will depend, then, on the geometry of the channel. That is, the larger the ship, the broader the turns must be for navigation. If the channel is characterized by tight turns, then no matter what the channel depth or width, it is unlikely that very long ships will be able to use it.

Given all these considerations, it is possible to make the following estimate of the maximum impact kinetic energy that can be expected for a ship-bridge collision in a given waterway:

$$KE = f \times T_c \times (L_{oa} \times V_{max})^2 \text{ ft-lbs}$$

where

L_{oa} = ship's overall length (this formula assumes that the beam of the ship is related to the ship's length);
T_c = channel depth and assumed to be ship's draft;
V_{max} = speed in knots at time of impact and assumed to be maximum speed allowed or possible in channel;
f = factor that depends on ship type, varying from 0.17 for relatively narrow and fine ships (such as containerships) to 0.35 for wide and full ships (such as tankers).

In using this formula, it is recommended that the constant f be chosen within the range given, depending on the traffic, and that L_{oa}, or overall length, correspond to the maximum length of ship that can traverse the waterway under the bridge. Field observations or simulator studies with "man in the loop" can be used to determine the design speeds of selected vessel types and sizes.

The Ship in the Waterway

The danger posed to a bridge by a ship plying the waterway is like that posed to a lamppost on the side of the road by a car traveling on a highway. The hazard not only involves the mass and speed of the car or ship (as discussed in the preceding section) but also the characteristics of the highway or channel. If the highway has twists, turns, narrow lanes, and blind spots, the car is at greater risk of an accident, and the risk may increase with rain, snow, or ice. Analogously,

some waterways are more difficult to navigate than others. Furthermore, the steerability and responsiveness of cars and vessels can vary. For vessels, a distinction is made between inherent controllability (steering and maneuvering characteristics without human control) and piloted controllability.* Recent analyses show wide differences in the inherent controllability of vessels (Barr and Miller, 1983).

Research has been undertaken in the last 10 years to determine the effects of the geometry and layout of waterways, the inherent controllability of vessels, and the role of the pilot in successful navigation of channels. Much of this research has involved measurement of ship trajectories in large marine simulators, and some has concentrated on model tests. A brief summary is given in succeeding sections of the research findings important to understanding ship-bridge collisions. Detailed information can be found in a recent publication of the Society of Naval Architects and Marine Engineers (1983).

Squat

Squat, or sinkage of a ship in motion, is an important factor that is affected by the depth and the width of channel, and by ship maneuvers. An increase in squat reduces underkeel clearance and the maneuverability of the ship.

Controllability

Vertical and horizontal excursions of a ship may be very great in response to wave, swell, wind, and currents in the unprotected waters of a port or harbor entrance. The effect of winds on lightly laden ships is important throughout a waterway.

Oscillations develop slowly when ships pass or overtake one another, negotiate turns, or move off the channel centerline. The channel must have sufficient room for the ship to recover from these oscillations.

Turns in the channel which have the inside angle of the turn truncated (called a "cutoff" turn) are much easier to navigate than noncutoff turns. Figure 5 shows one turn of each type. The tracks of simulated transits through the cutoff turn show less variability with different pilots. Those for the noncutoff turn show a much greater variability and, in some cases, grounding of the ship (or by extension, collision with a bridge pier located adjacent to the channel in this reach).

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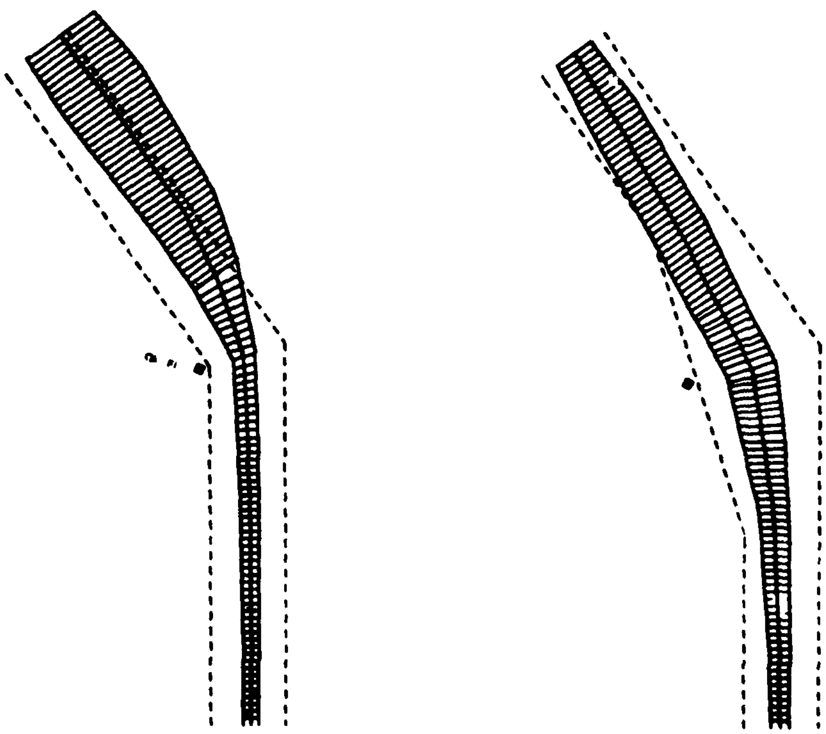
*Some important aspects of piloted controllability, including aids to navigation, are treated in Chapter 11, "Preventive Systems."

Figure 5 Comparison of maneuvering in cutoff and noncutoff turns*



35° noncutoff turn: variability of ship tracks (piloted simulator)

35° cutoff turn: variability of ship tracks (piloted simulator)

*SOURCE: William R. Bertsche and Roger C. Cook (1980), "A Systematic Approach for Evaluation of Port Development and Operations Problems Utilizing Real Time Simulation," CAORF Port Studies, Presentations made at the Fourth Annual CAORF Symposium, Kings Point, New York, September 29-30, 1980 (Kings Point, N.Y.: National Maritime Research Center).

Underkeel Clearance

One of the most important discoveries regarding the behavior of ships in restricted waters has been the observation that the maneuvering characteristics of ships change dramatically with the underkeel clearance. The effect of decreasing water depth on turning performance is shown in Figure 6. These figures show the behavior of tankers, but that of cargo ships is similar. In deep water, most ships are directionally stable and can turn in a circle with a diameter of 2 to 3 times the length of the ship. These turns are accompanied by a very noticeable yaw angle relative to the direction of travel. In waters where the underkeel clearance is of the order of half the ship's draft, many ships tend to become directionally unstable. That is, they are difficult to keep travelling in a straight line and require constant steering. As shown in Figures 6a and 6c, a ship can start into a turn much sooner at a channel depth to ship draft ratio of 1.5. When the underkeel clearance becomes very small, the ship becomes directionally stable again and is very difficult to turn, as can be seen in these figures. Notice also that in the case of very little underkeel clearance, the ship no longer yaws heavily and remains aligned with the direction of motion. The minimum radius of turn in this situation is usually proportional to the length of the ship. The underkeel clearance of many laden ships in the channels of the United States is far less than this--it may be as little as 2.5 percent of ship's draft (Marine Board, 1983).

Loading of Ships

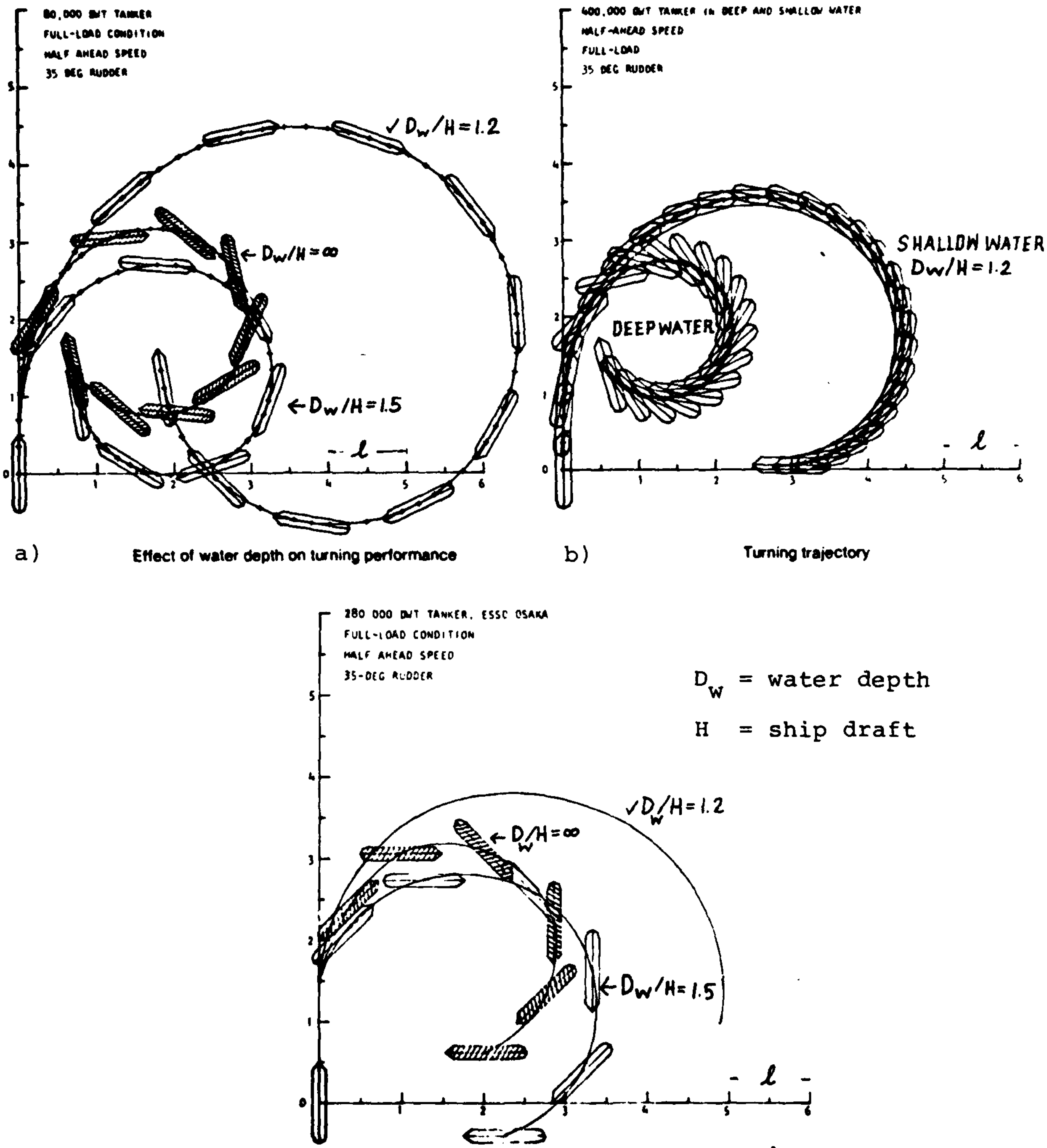
Ships riding in ballast may have very shallow drafts: the Summit Venture (fully loaded draft, 23 ft) at the time of its collision with the Sunshine Skyway Bridge had deballasted in preparation to load cargo at the Port of Tampa and had a forward draft of just 9.4 ft, a midship draft of 15.5 ft, and an aft draft of about 21.5 ft (National Transportation Safety Board, 1981b). Ships in ballast have reduced turning ability (Eda et al., 1979) and because of their reduced drafts may wander far from the navigational channel in shallow water.

A ship collision risk assessment for the Sunshine Skyway Bridge replacement (COWIconsult, Inc., 1981) noted that the most dangerous ships for that bridge "are ships in ballast. They still have considerable impact force,* which is a danger to the bridge piers [in] shallow water, and they lie high in the water, which is a danger to the superstructure" (and, it may be added, to the slender bridge-pier shafts that frequently surmount the solid pier section near the waterline).

---

*The maximum design energy of an 85,000 DWT cargo vessel in ballast (average draft 15.5 ft), under way at 10 knots, was estimated by Knott (1981) as being equivalent to that of five fully loaded 727s at maximum landing speed of 120 knots.

Figure 6   Turning trajectories for various ships with changing water depth*



a) Effect of water depth on turning performance

b) Turning trajectory

c) **Effect of water depth on turning performance (*Esso Osaka* trial results in deep and shallow water)**

*SOURCE: H. Eda, R. Falls, and D. A. Walden (1979), "Ship Maneuvering Safety Studies," <u>SNAME Trans.</u>, <u>87</u>: 231.

Decisions about ballast are made by ships' masters on the basis of economic and safety factors, and the stipulations of foreign ports and canals (COWIconsult, Inc., 1981; Guy, 1982). There are no regulatory requirements for amount of ballasting in the United States, but some are demanded by local pilots associations--for example, to clear loading tipples or low bridges.

Stopping

The preferred maneuver to stop a ship in deep water (to avert collision, for example) is by steering it into a tight turn, stopping the propeller, and once in the turn, ordering full astern. Control can be maintained over the ship by this maneuver. On the other hand, a "crash stop," or reversal to full astern of an underway ship, eliminates the propeller race, and the ship becomes an unguided missile. In navigational channels, the turning radius of a vessel increases so dramatically with decreasing underkeel clearance that a tight circle will probably be impossible, and far less reduction in speed can be expected than in deep water.

The uncontrollability of a ship attempting "crash astern" is pronounced in shallow water: the heading change of a large tanker (at half-astern from modest approach speed) was found to increase from 18° in deep water to 88° with 20 percent underkeel clearance (Crane, 1979).

While tug assistance is provided or required in various navigational channels or situations for steering large ships, even a number of tugs will be no more effective in stopping a large ship than the ship itself (Crane, 1973). It should also be noted that anchor systems are not designed as braking systems.

The only significant means within the control of ship pilots in navigational channels to reduce the stopping distance, should emergency maneuvers be required, is slow speeds. Controllability is maintained by short bursts of higher propeller rpm ("kicking").

7

DYNAMICS OF SHIP COLLISIONS

Types of Collision

Two different types of collision must be considered: those which are head on and those which result from a glancing blow.

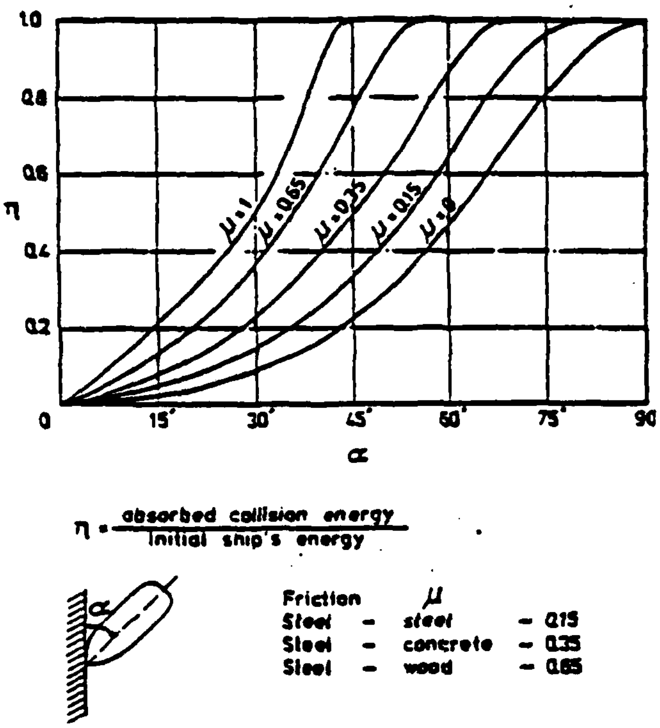
In head-on collisions, all of the kinetic energy of the ship must be expended. This will somehow involve crushing some of the structure of the ship's bow as well as that of the bridge's protection system (if it has one) or structure. A cursory examination of the bows of various typical ships reveals great variation. Faster ships, such as containerships, have fine, pointed bow shapes above water and will probably have a bulbous bow below water. The bows of these ships will be able to crush more easily than the blunt and strong bows of tankers or bulk carriers.

Some simple techniques for determining the maximum impact forces based on energy methods have been developed by Minorsky (1959, 1982), Woisin (1971, 1976, 1978), and Woisin and Gerlach (1970). A detailed analysis of the actual load imparted to the bridge structure requires a complicated, nonlinear finite-element computation of the interaction between the actual ship structure and the bridge protection system. Finite-element routines developed for ship-ship collisions may be useful in these analyses (see, for example, Chang, 1983).

The glancing blow is more difficult to analyze than the head-on collision, since the amount of kinetic energy transferred cannot be easily estimated. An analysis of an oblique collision of a ship against a flat wall was made by Saul and Svensson (1982a,b). The results of this analysis are shown in Figure 7. This figure shows the estimate of the ratio of the kinetic energy absorbed to the initial ship's kinetic energy as a function of the impact angle and the coefficient of friction between the ship and the wall.

Since this figure represents perhaps the only current study of oblique collisions of ships and bridges, it is important to underline the limitations in its use. In the derivation of the analysis illustrated in Figure 7, assumptions were made concerning the nature of effects on the dynamics of the fluid around the ship that may not be true in most situations of concern. First, the transverse added mass of the fluid was estimated to be 50 percent of the ship's mass. Although this value is reasonable for a ship in deep water, the transverse added mass can be as much as an order of magnitude larger if the

Figure 7   Part of collision energy to be absorbed by the ship and/or pier in relation to collision angle, α, and friction, μ *



Note: This figure results from a theory that ignores the increase in transverse added mass with decreasing underkeel clearance and the effect of cross-flow drag. Both effects will tend to increase the kinetic energy absorbed in an oblique collision. It applies only to impacts against wall-like structures that have a length greater than the impact area, and may not apply to the impact against a single shaft of small diameter.

*SOURCE: R. Saul and H. Svensson (1982), "On the Theory of Ship Collision against Bridge Piers," <u>IABSE Proc.</u>, <u>51/82</u>: 34.

underkeel clearance is very small. Second, very substantial hydrodynamic forces can result from a fluid velocity transverse to the ship's centerline. These forces are also ignored in the derivation leading to this figure. The net effect is that Figure 7 underestimates the amount of kinetic energy that will be absorbed by a bridge structure when hit obliquely by a ship with small underkeel clearance.

As seen in Figure 6, ships that do have significant underkeel clearance (such as ships in ballast) develop large yaw angles relative to the direction of travel during maneuvers. As a result, if such a ship is trying to avoid the collision just before the impact, it may well have a large enough yaw angle to cause the impact to be considerably aft of the bow. (This was, in fact, the orientation of the *Titanic* in its collision with the iceberg.) The importance of this collision mode is that it represents a much greater danger to the ship and its cargo than a head-on collision. Collisions by yawed ships are not considered in the analysis illustrated in Figure 7.

Finally, most of the bridge piers of interest are not wall-like: the scale of a struck pier may be the same as the bow of the ship that strikes it. In this case, an analysis of the kinetic energy transferred must address both the impact angle and the impact location on the pier. If the pier is smaller in diameter than the ship's beam, it may be possible for the ship to wrap itself around the pier.

In conclusion, then, it is not easy to estimate the amount of energy that will be absorbed by a bridge structure in a glancing blow. If the ship involved in the impact has little underkeel clearance, it seems prudent to assume that the whole kinetic energy will be absorbed.

Calculations of Collision Forces

An upper bound for the impact force may be estimated from consideration of the force required to deform the ship in a direct head-on collision with a rigid obstruction.

Collision tests using scale models of passenger liners, tankers, and containerships were conducted in Germany between 1967 and 1976, expanding the classic work of Minorsky (1959) in the United States. The models used represented vessels up to 195,000 DWT capacity (Woisin, 1971, 1976, 1979; Woisin and Gerlach, 1970).* The results indicate that the maximum impact force, P_{max}, "increases at the beginning of the impact for approximately 0.1 second to 0.2 second to double the amount" of the median impact force P_m. P_m is calculated as follows:

$$P_m = \frac{\delta KE}{a}$$

*It may be noted that this research addressed high-energy collisions. The interagency Ship Structure Committee has reviewed available techniques and needed research in low-energy ship-ship collisions (Ship Structure Committee, 1979).

where δKE = transmitted kinetic, or collision, energy and a is the interval over which damage occurs.

Woisin investigated the relation between impact force and ship size for bulk carriers. His work led to the conclusion that the maximum impact force, P_{max}, for collision of bulk carriers with stiff piers follows the formula (Saul and Svensson, 1982a)

$$P_{max} \approx 90(W)^{\frac{1}{2}} \pm 50\%*$$

where P_{max} is the maximum impact force in short tons (2000 lbs) and W is the ship displacement in long tons (2200 lbs). The variation of $\pm$ 50% comes from the variability of bow shape, structure, and stiffness among ships of the same size (including the variation of stiffness caused by differences in the extent to which a ship's forepeak is ballasted with water).

Impact energy has been calculated for ship-bridge collisions using a slightly different method (Greiner Engineering Sciences, Inc., 1982), following Saul and Svensson (1982a), Japanese National Section of PIANC (1980),Derucher and Heins (1979):

$$KE = \frac{KW}{2g} \cdot V^2 \cdot Ce \cdot Cm$$

where KE = effective kinetic energy of ship (ton-feet, or kip-feet);
K = coefficient depending on units of measurement
g = acceleration of gravity (32.2 ft/s^2);
W = displacement tonnage of ship (long tons);
V = approach velocity of ship (ft/s or knots);
Ce = eccentricity factor;
Cm = hydrodynamic mass coefficient.

The eccentricity factor, Ce, is determined by the angle of impact of the particular collision; in a head-on collision, Ce = 1.0. As indicated in the preceding section, more research is needed to understand the nature of this factor. The hydrodynamic mass coefficient, Cm, accounts for the mass of water that is moving with the ship, estimated to be 5 percent to 10 percent of the ship's displacement mass when the ship is on a straight course. It can be 50 percent to 80 percent of the displacement mass of a ship that is moving laterally in deep water, and for a ship with little underkeel clearance, the lateral hydrodynamic mass factor may be more than 500 percent. Recent model tests (Ball and Markham, 1982) indicate that for the underkeel clearances of

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*Woisin's formula, $P_{max} = 0.88\ (DWT)^{1/2} \pm 50\%$, gives P_{max} in meganewtons, based on deadweight tonnage for bulk carriers. The formula stated here gives P_{max} in short tons, assuming deadweight tonnage = 85% of displacement.

2.5 percent to 5 percent typical of large ships in channels of the United States, the added hydrodynamic mass may be 1100 percent to 1500 percent of ship's mass.

The amount of impact energy absorbed by the pier and by the ship varies according to the stiffness of the pier, the shape and stiffness of the portion of the ship that hits the pier, the size of the ship, and (in second order) the ship's kinetic energy. The stiffnesses of the elements that strike each other largely determine the impact force, P.

A study of the collision of the 31,800 DWT* tanker Gerd Maersk with Newport Bridge in Rhode Island in February 1981 calculated the average ship-collision forces to be about 6000 tons, applied for a duration of about 2 s (seconds) in a head-on collision at vessel speed of about 6 knots. This calculation was derived from observations that the ship had come to a complete stop and that the crushing of its bow shortened the ship's length by 11 ft (Kuesel, 1983).

Recent Work

A number of reports on theoretical and model studies of the forces developed in crushing or diverting ships, and on design criteria for bridges and offshore oil drilling platforms, are contained in the proceedings of the International Association for Bridge and Structural Engineering (IABSE) colloquium on ship collision with bridges and offshore structures, held in Copenhagen May-June 1983.** Minorsky (1982) describes analyses based on aircraft frame analysis methods, which were used to verify German tests made on a model of a 195,000 DWT oil tanker. These indicated that prototype forces greater than 20,000 tons could be developed in a head-on collision that might crush the bow in to a depth of as much as 50 ft. Much research and evaluation of ship collision impacts has been stimulated by the offshore oil development in the North Sea. This has been codified by det Norske Veritas, as reported by Fjeld (1982). The Nordic Road Council (NRC) has adapted this material to a chart of recommended impact forces for the design of bridge piers (Figure 8). This relates vessel size to draft, and design force to a combination of draft (or channel depth) and ship speed. In general, the NRC recommendations are somewhat less than those given by the empirical formula cited in the preceding section. However, the NRC design forces are static loads (applied at the waterline), while the empirical formula is for an instantaneous maximum load, approximately twice the average load developed during the ship deformation.

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*Displacement = 45,000 (long) tons.

**Introductory Report, August 1982; Preliminary Report, March 1983; Final Report, in press.

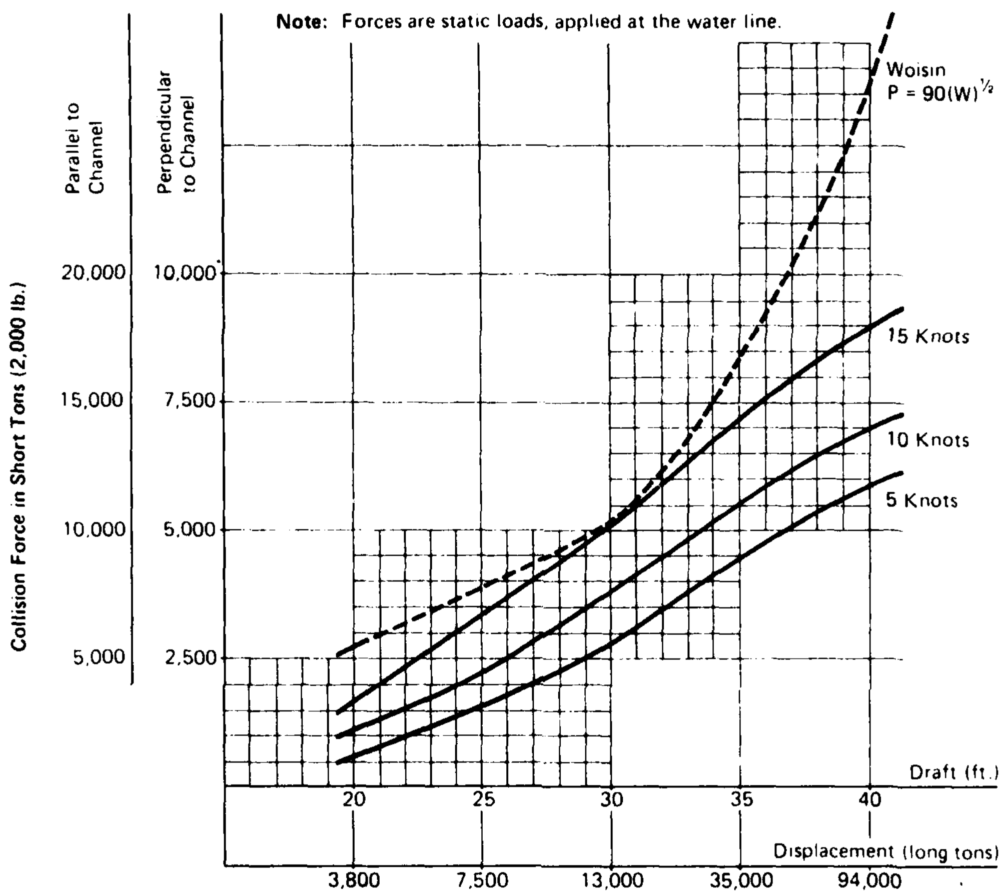


Figure 8 Recommended ship collision design forces for bridge piers, Nordic Road Council, 1975*

*SOURCE: Adapted from W. Von Olnhausen (1983), "Ship Collisions with Bridges in Sweden," IABSE Colloquium, Preliminary Report, pp. 409-416.

Rasmussen (1982) and Von Olnhausen (1983) give examples of the application of the NRC rules to the design of bridges in Denmark and Sweden.

For the Sunshine Skyway replacement bridge in Florida, ship impact loads ranging from 6000 tons for the main piers to 500 tons for approach pile bents were adopted (Greiner Engineering Sciences, Inc., 1982). In addition, protective islands or dolphins are to be provided for several piers on each side of the navigational channel.

For the proposed Øresund Bridge between Denmark and Sweden, the design criteria are based on a collision of a 40,000 DWT tanker at 16 knots (Von Olnhausen, 1983). The corresponding collision force is given as 150 meganewtons (MN), equivalent to 16,650 short tons. Von Ohnhausen also calculates a collision force of 240 MN (26,640 short tons) for a 100,000 DWT tanker.

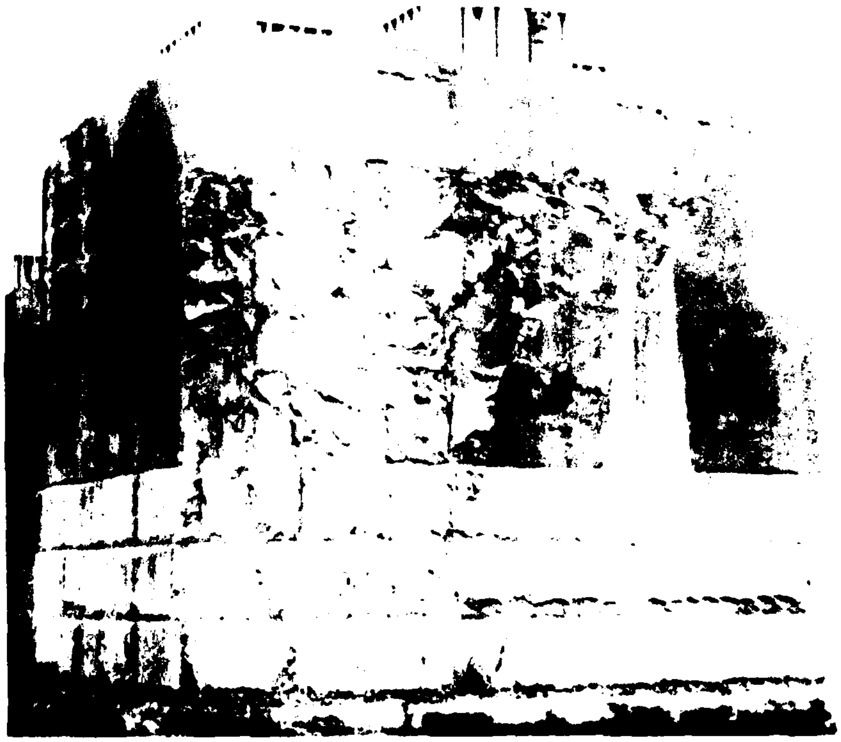
For the Faroes bridges under construction in Denmark, collision forces ranging from 7 MN to 20 MN (780 to 2220 short tons) per pier, depending on the exposure of the pier, were adopted for design (Jensen and Sorensen, 1983). These forces were based on a "characteristic ship" of 2250 DWT at a speed of 6.25 m/s (approximately 12 knots).

Fjeld (1982) lists the following additional cases of collision forces used for bridge design:

Bridge	Ship Size[a]	Ship Velocity	Design Force[b]
Öland Bridge, Sweden	--	--	5,000 T
Øresund Bridge, Denmark-Sweden	50,000 T	9.4 m/s (18.2 kn)	14,200 T
Great Belt Bridge, Denmark			
Navigation Spans	250,000 DWT	--	44,000 T
Side Spans	4,000 DWT	--	6,000 T
Bahrain/Saudi Arabia Bridge	20,000 T	4.2 m/s (8.2 kn)	5,600 T
Luling Bridge, Louisiana	40,000 DWT	3.5 m/s (6.8 kn)	27,000 T

[a] Displacement, except as noted
[b] Metric (long) tons

These design criteria are based on collision with an unyielding, wall-like bridge pier, in which the entire kinetic energy is absorbed by deformation of the ship and the force delivered to the pier depends on the crushing length of the ship's bow. Various forms of protective construction, as described in Chapter 10, "Protective Systems," can be used to absorb greater or lesser proportions of the total kinetic energy and to divert the course of the ship so as to avert head-on collisions, thereby reducing the forces delivered to the bridge piers.



Collision of Gerd Maersk and Newport Bridge, Rhode Island--ship's bow shortened 11 ft, relatively minor damage to massive bridge pier

Photographs: Parsons, Brinckerhoff, Quade & Douglas, Inc.

8

SITING AND DESIGN OF BRIDGES TO REDUCE SHIP IMPACTS

Bridge Siting

In considering alternative locations for new overwater bridges, attention should be given to existing problems of navigation in the waterway and to the relative hazards of different locations for the waterway crossing. Preference should be given, for example, to sites remote from bends or turns in the waterway. Ship pilots associations and the U.S. Coast Guard should be consulted during the phase of bridge design in which alternative sites are investigated. This is strongly recommended by the Federal Highway Administration (see Chapter 13, "Legislative and Institutional Framework") and required by the U.S. Army Corps of Engineers for design of new navigational channels or major improvements.

Bridge Piers

Location

To minimize construction costs, a bridge designer usually begins by siting the piers for the main span as close to the channel lines as possible. This, however, can raise the risk of major ship collisions to an unacceptable level. Bridge designs that call for relatively long spans and high clearances reduce the risk of collision. Where conditions permit, the main piers should be placed on land, or artificial islands, or in very shallow water that allows ships to ground before reaching the pier. If the piers cannot be placed on land or in shallow water, the choices are to design the pier to resist the impact of a collision, or to provide a free-standing protective structure to absorb the impact and divert the ship away from the pier. Alternative structures and devices are described in Chapter 10, "Protective Systems." The feasibility and cost of these alternatives depend heavily on the depth of water and the nature of the foundation materials. They should be considered in the design and layout of a bridge together with other factors.

Design of Bridge Piers

As noted, the more massive the bridge pier, the less damage it will suffer in a collision. Thus, in designing the piers, consideration should be given to the relative masses of the piers and the vessels using the waterway. Within the constraints of geotechnics, seismic activity, and economics, the piers should be as massive as possible.

The bridge pier itself can be configured to reduce the effects of ship collision from a large vessel. For example, by extending the footing block at a suitable underwater elevation, say, 20 ft below water, the bow of the ship will engage the footing at that elevation: the footing will absorb considerable energy before the ship hits the pier shaft. This reduces the overturning moment significantly, and sliding becomes the critical mode. The enlarged footing block may also be advantageous in shear transfer into the soil (detailed in the succeeding chapter).

It is advisable to provide a solid wall or "crash block" up to the height of the forepeak of the highest expected ship riding in ballast on a high tide. This protects the pier against the possibility of the ship's superstructure's catching a thin pier shaft (as in the Sunshine Skyway disaster) or a steel column (as in the collision against the Mount Hope Bridge). A pointed "cutwater" nose on the crash block will reduce the opportunity for a head-on collision, and the angular impact against the bevelled side of the cutwater may be relatively effective in diverting a ship riding high in ballast (Figure 9).

Placing controlled rock fill around the pier base may somewhat increase its sliding resistance by providing passive pressure against the pier.

The footing block (especially if extended) may be configured to deflect the ship--for example, tapered and sloped, so that the bow of the ship rises slightly and is forced to veer off.

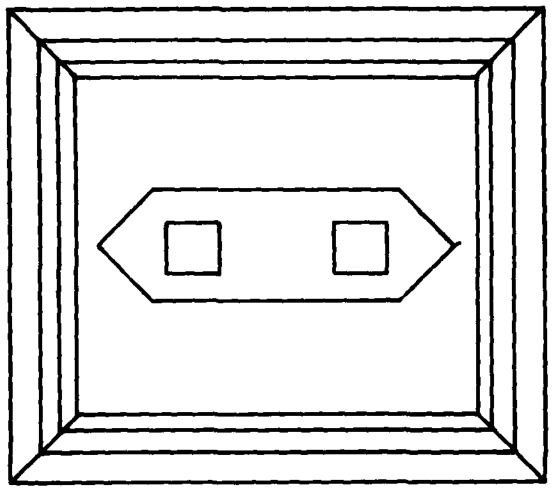
The pier should be embedded into the natural bottom soils for lateral passive resistance. Vertical piles that are free-standing in water, or embedded in soft soils, offer poor lateral resistance to collision loads. If the natural soils are soft, their passive resistance will also be small. In this case, removal of the soft soils and replacement with better materials may be the solution. The best lateral resistance is, of course, provided by embedding the entire footing in an artificial island up to the water surface.

The pier shaft has proved especially vulnerable to lateral impact. Ductility can be greatly increased by following these design steps used in offshore structures:

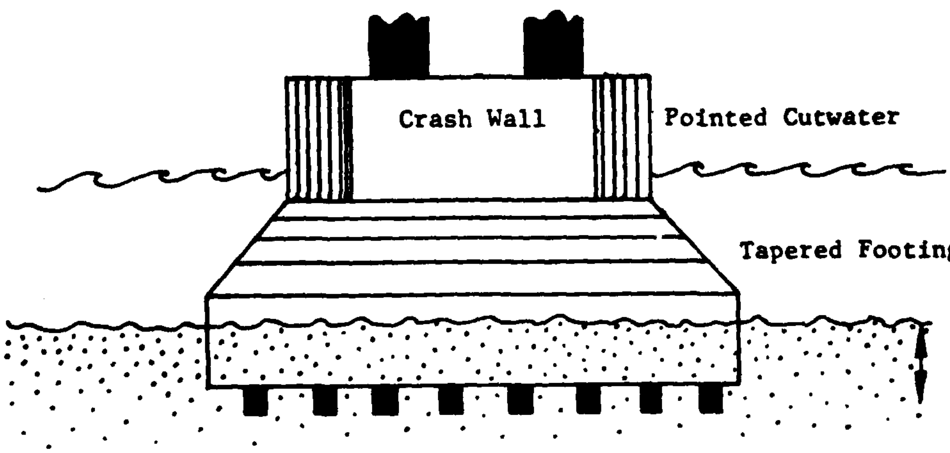
- o Splice vertical bars at different elevations;
- o Double the normal splice lengths to prevent failure in bond under impact; and
- o Provide heavy confining steel, similar to that required for seismic design of columns.

Pile-supported piers for shorter spans and approach bridges in areas subject to seismic activity are often designed for maximum ductility in earthquakes, using all vertical piles. But if ship

Figure 9   Crash wall and nose for bridge piers



Plan View



collisions are given the same emphasis as earthquakes, stiffness and allowable deformation under lateral force may require the use of larger-diameter piles or the provision of increased passive resistance.

Bridge Superstructure

Vertical Clearance

A number of collisions have involved high masts or spars striking the lower edge of the bridge superstructure. In establishing the vertical clearance, consideration should be given to the design vessels' riding in ballast on a high tide.

Protection

Damages in ship-bridge collisions are frequently augmented by the span's falling off its supports, just as in an earthquake. To mitigate this additional damage, longitudinal earthquake restrainers can be provided, as well as lateral stops on the end of cap girders. Chain restrainers to catch a span or girder after it has moved off its bearing may prevent complete loss of the span.

Deepwater Spans Outside Main Channel

Bridge designers have traditionally given little consideration to the possibility of ships operating outside the channel. Yet, the records of major ship-bridge collisions worldwide (Table 2) show that a majority of the serious collapses involved ships that for a variety of reasons strayed out of the channel by distances of up to a mile. The hazards of ship collisions extend the entire width of the waterway in which a substantial ship may float in ballast without running aground. This may be taken to include all waters in which the depth at high tide exceeds 20 ft, unless protected by fixed natural or artificial devices.

Loaded barges of considerable mass may float in 10 ft of water, and if unloaded in 5 ft, and the possibility of accidental impact from such vessels should also be considered. Pilots in the Houston Ship Channel, for example, are concerned about the piers of a new highway bridge that are in just 8 ft of water (Kliewer, 1982). A barge carrying hazardous chemicals may scrape against the unprotected concrete piers, and sparking may ignite the cargo.

It is usually impractical and prohibitively expensive to provide complete collision protection to all parts of a long bridge over wide, deep waters. Some evaluation of the justifiable additional expense (beyond that for a minimum structure with no provisions for collision protection) may be made through techniques of statistical risk analysis. (These techniques are briefly described in Chapter 12, "Estimation of Risk and Evaluation of Mitigating Alternatives.")

Most long-span bridges involve a structural configuration of a main channel span flanked by two anchor arms or principal spans, all

supported by four piers. If the four piers are all located in deep water, it is essential that each be given similar ship-collision protection to preserve the integrity and continuity of the three-span unit.

Where the risk of ship-bridge collisions is judged to be relatively high, preference should be given to designs that

- o Provide relatively long spans over deep waters;
- o Provide relatively high superstructure clearances over deep waters;
- o Employ redundant structural systems (e.g., multiple shafted or slab piers, rather than twin thin columns; 3-pile bents for trestle structures, rather than 2-pile bents); and
- o Provide some form of protective construction for approach-span piers.

For low-level approach spans, where the risk of a ship's striking the superstructure is greater than that of collision against the pier, it is preferable to use relatively short spans of standard design and to stockpile spare superstructure span units to facilitate rapid repair if a span is lost. This procedure is followed at the Lake Pontchartrain and Chesapeake Bay bridges, both of which have suffered numerous accidents.

For crossings of very wide, deep waters, where navigation is not physically confined to dredged channels, consideration may be given to bridge layouts that provide separate channels for inbound and outbound ship traffic. Examples include the San Francisco-Oakland Bay Bridge and the San Diego-Coronado Bridge, both in California.

Structural Considerations for Design of New Bridges

Several combinations of vessel size, configuration, and velocity should be considered in the design phase. One case should represent the heaviest ship expected regularly, fully laden, operating at a speed normally used by such ships in that channel. A second case should represent the same ship in ballast, with reduced mass but riding high in the water, also at normal operating speed. A third case should represent shallow-draft vessels that might override submerged or floating protective systems (if used).

Each of these cases represents a "maximum collision," to be used for an ultimate capacity analysis. Reduced speeds, corresponding to those customarily used under difficult operating conditions, are appropriate to analysis of a "normal collision."

A sector of design courses for the ship should be selected, ranging either side of the nominal channel course. In determining the sector width, consideration should be given to the effects of tides, currents, and winds, as well as to the alignment of the channel on both sides of the bridge and the consequent difficulty of navigating a true course.

From these considerations may be derived a series of design masses and velocities, a range of heights for application of the collision

forces (relative to high or storm tide, and to low tide) and a range of directions about the nominal channel bearing. The combinations of design masses and velocities correspond to a series of design kinetic energies to be considered.

The proportion of the design kinetic energy absorbed in the collision depends on whether the ship is brought to a complete stop or merely diverted from its course at impact. The effects of added hydrodynamic mass must be considered, as indicated in the preceding chapter. Geometric layouts of the ship, pier, and protective construction will give a basis for proportioning the design kinetic energy at various locations around the perimeter of the protective structure. The further allocation of the collision kinetic energy among the ship, the protective structure, and (except where the latter is free-standing) the bridge pier depends on their relative rigidities (or compliances). Foundation conditions, as detailed in the succeeding section, may have important influences on the rigidity of structural elements.

The forces applied to the protective structure and the bridge pier can then be estimated by the procedures outlined in the preceding chapter. The data base and methodology are not sufficiently developed to provide numerical design criteria: each case must be evaluated subjectively by the designer. If it is desired to limit the damage to the ship, the rigidity of protective structures should be such that they deform substantially at a force considerably below that required to crush the ship structure.

One effective design concept (see Chapter 10, "Protective Systems") is a crushable protective structure surrounding the pier that will limit the force applied to the pier in a ship collision to values below damaging force. The protective structure is sacrificed in the event of the design accident. It must have a sufficient crushing length to absorb the design kinetic energy. This concept was used on the Francis Scott Key Bridge on the Outer Crossing of Baltimore Harbor and proved effective in absorbing a direct collision shortly after the bridge was completed.

9

GEOTECHNICAL ASPECTS OF SHIP COLLISIONS WITH BRIDGE PIERS

The impact of the ship against the pier develops lateral shear and overturning effects which must ultimately be resisted by the soil in two principal modes: lateral displacement and tilting.

Lateral displacement is a result of shear along the base. For example, a massive pier founded on dense sand or sand/gravel conglomerate resists lateral displacement primarily by friction, whereas one bearing on clay hardpan resists such failure by direct shear. Resistance is also provided by the passive pressure in the soils behind the pier: failure is accompanied by upward sliding of the passive wedge.

The two principal types of resistance are not fully additive, owing to the different degrees of deformation needed to develop the resistance, and this is particularly true of the pseudoelastic range.

The second mode, tilting, is essentially a bearing failure owing to moment. It is resisted by high bearing pressures which develop under the far side and, to a minor degree, by the temporary suction and frictional resistance on the near (impact) side.

The distribution of such bearing pressures is not triangular, as often shown in introductory engineering texts, but rather parabolic, because of the strains that develop. The Brinch-Hansen method (Bjerrum, 1973; det Norske Veritas, 1981; Federation Internationale de la Precontrainte, 1979) is generally used to compute the resisting forces and bearing pressures under the combined effect of vertical loads and high lateral forces.

The greater the vertical dead load--the more massive the pier--the greater the area participating in the bearing resistance, and hence, the greater the resistance to tilt.

With relatively small lateral forces, such as those due to wind, these soil responses are essentially elastic: the pier displaces a small distance and then returns. Larger forces, such as those generated in a ship collision, may produce permanent displacements and tilt.

Many bridge piers are founded on piling. In areas subject to seismic activity, these are usually vertical or near-vertical, to minimize earthquake response in the pier. They resist the moment from ship collision by the couple developed between the near and far piling; the far piling acting in compression and the near piling in tension. This can only be properly developed if tension ties exist between the

piles and the pier footing. Most pier footings are rigid enough in themselves to transmit the moment and develop the pile reactions.

If piles develop their resistances by friction or bearing on clays or similar materials, the distribution of forces will be other than triangular, especially near ultimate. A modified Brinch-Hansen approach may be used to determine pile reaction forces.

The pier footing block should be designed to develop the ultimate capacity of the piles without punching shear failure.

The more serious mode of reaction for pile-supported piers is lateral displacement, which causes bending in the piles, typically an "S" curvature if the piles are free-standing in water or embedded in soft soils. Piles resist lateral displacement by the passive resistance of the soil behind them. This can be approximated by a P/Y analysis (force: displacement as a function of depth and pile stiffness), which has become a standard method for determining the lateral resistance of piles for offshore structures (American Petroleum Institute, 1982). The larger the pile diameter and the stiffer the pile, the greater the resistance.

Failure under this mode usually occurs by structural collapse of the piles under combined axial load and curvature. In this case, the critical piles will be those on the far side, which have a high axial load (dead load augmented by the resistance to tilting), as well as the curvature.

With concrete piles, failure will occur by crushing. Heavy confinement of the concrete by spiral reinforcing steel can increase the strain capacity significantly.

With steel piles, ultimate failure will occur by buckling. The capacity of pipe piles can be greatly increased by sand or concrete fill. Steel H-piles can be oriented to provide maximum resistance to bending.

Pile-supported piers also develop some small resistance to displacement owing to the passive resistance of the soils surrounding the footing block, but this effect is usually small. An exception is the case where the pier footing is embedded in a relatively firm stratum, even though pilings are employed to resist the vertical loads.

Batter piles (raker piles) are sometimes used for bridge piers on the East and Gulf coasts, but seldom in areas of seismic activity because of their extreme rigidity and adverse performance in earthquakes. If used, they provide rigid but somewhat brittle resistance to ship impacts.

To develop their full resistance, the connection between pairs of batter piles must be adequate to transmit shear and moment around the intersection. Punching shear and pull-out must be prevented.

Piles do not shear through the soil except in extremely weak muds.

Inclined piles do not stay in simple axial compression or tension under high lateral force but displace with bending as well. Hence, structural failure will usually occur in the compression pile under combined axial load and moment.

Scour due to bottom currents and waves can seriously reduce the capacity of a pier for large lateral forces such as those due to ship collision. Scour removes the upper soils surrounding the pier, thus reducing passive resistance. More seriously, it may undermine the

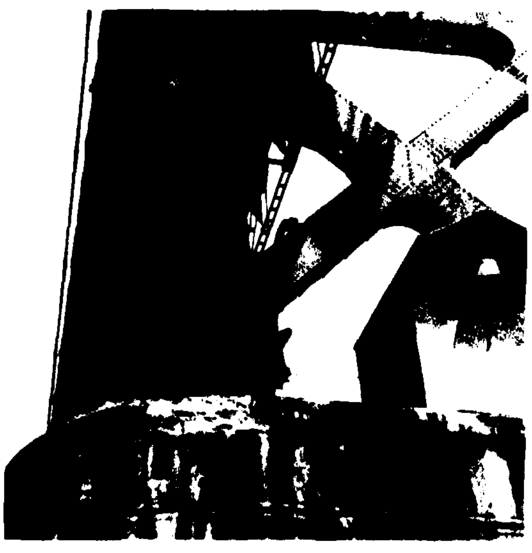
pier, with the result of increasing the moment imposed on the piles and allowing greater deflections. This in turn increases the P-Delta effect (the moment produced in the pile by its axial load acting eccentrically due to the deflection) in the piles and may lead to their premature failure under combined vertical loads and moment.

It is important, therefore, to provide adequate scour protection and to inspect it at regular intervals. Recently, an underwater exposure of the main piers of the Richmond-San Rafael Bridge, in 60 ft to 80 ft of water, showed 5 ft to 10 ft of scour under the piers in the mud bottom, even though small rock backfill had been placed under and around the pier at the time of construction. This scour had exposed the tops of the steel H-piles under the concrete pier and greatly reduced the resistance to lateral forces. The piers have now, of course, been properly backfilled.

Scour under the footings of older bridges founded on timber piles may have exposed them to attack by marine borers. In addition to the effects on vertical load capacity, this can seriously erode their capacity for lateral resistance to ship-collision forces.

Energy-absorption capacity is a function of the resisting force times the displacement. As noted, large soil displacements are highly nonlinear with respect to resistance.

The pier can absorb energy by displacement and tilting, but as indicated, this may lead to geometric instability or to failures in individual structural components due to combined stresses (strains). These large deformations will be essentially inelastic and therefore permanent.



Mt. Hope Bridge, Rhode Island,
damage from glancing collision
with tanker

Photographs:
Steinman Boynton Gronquist
& Birdsall

10

PROTECTIVE SYSTEMS

Bridge Protection

Protection to bridge piers against ship collision can take either of two forms. One is provision of independent structures that will encounter the ship and deflect it or stop it, while absorbing the energy of impact before the ship hits the pier. This category includes embankments and berms (protective islands), moored cable arrays, independent structural barriers, dolphins and protective cells, and moored pontoons.

The second category is that of deflecting and energy-absorbing devices affixed to the pier itself, designed to deflect the ship from exerting its full impact force or to absorb the energy of impact through deformation, reducing the maximum force exerted on the pier to acceptable levels. This category includes fenders of timber, rubber, and steel; sliding blocks of large mass; and hydraulic-type or mechanical fenders (referred to collectively as "fenders" in this report).

A detailed review can be found in Saul and Svensson (1981, 1982a).

Choice of Systems

Decisions about which of these many types to employ depend on the available space, bathymetry, soils, types and sizes of ships, type of bridge piers, seismicity, ice, fog, tides, and many other factors. There has been some confusion whether primary consideration should be given to protecting both pier and vessel from damage during grazing-type impacts in normal service or to protecting the bridge pier against the extraordinary event of direct collision from a high-energy vessel. Fenders are obviously suited to the first approach, whereas separate structures are best suited to the second.

Consideration must be given to the damage to the ship in the extreme case: Will the ship sink in the channel and block it? Will oil tanks rupture and cause heavy pollution?

In deciding the type of protective structure, the energy-absorbing mechanisms of the ship may also be considered: crushing, buckling, etc., of ship plates and bow.

Independent Structures

Protective Islands These may consist of sand and gravel embankments, suitably armored (riprapped) against erosion by waves, currents, or propeller scour. While they need not extend above water for protective purposes, ship pilots will prefer that they be visible. Moreover, consideration must be given to the very shallow drafts at the bow of large ships riding in ballast on a high tide.

Protective embankments or islands exert a load on seafloor soils, leading to potential long-term settlement. The effect of this "downdrag" on the bridge pier and its piling must be considered.

The colliding ship tends to plow into the embankment and ride up on it. Resistance comes from the passive pressure of the soil against the ship's bow and sides, from friction of the bottom against the embankment, and from the lifting of the ship as it rides up on the embankment. This system of protection was proposed for the main piers of the Great Belt Bridge in Denmark.

Moored Cable Arrays A number of systems have been developed using cable arrays, supported by buoys at intervals and moored to anchors in the bottom. The buoys counter large differences in water level. The concept is that the bulbous bow of a tanker will engage the cable and be brought to a gradual stop by the stretch in the cable system and the dragging of the anchors. Such systems are being installed to protect the bridge piers of the Parana River bridges in Argentina.

The great uncertainty lies in whether the bow will engage. Many ships still have a clipper bow (no bulb) and even bulbous bows encountering the cable at an angle may fail to engage. Ships may ride over the cables with little resistance.

Other potential problems are that the cable may capsize a smaller vessel and that a snapped cable is a lethal weapon.

Independent Structural Barriers Pile-supported platforms, similar to concrete-wharf structures, protect the main piers of the Carquinez Bridge in California. Horizontally trussed frames of timber, steel, and concrete that are supported by vertical and batter piles have been used extensively: these resemble the nose dolphins of ferry slips and have been designed to permit extensive deformation and local failure as the ship penetrates successive resisting frames.

The concept is to mobilize an extensive system of piles and structure to resist an extreme concentrated force applied at any point.

The independent structural barriers tend to become rather large and expensive structures in themselves, with relatively high costs for repair after damage. The potential for fire during collision or from an unrelated cause must be considered. A fire in the timber protectors for the Richmond-San Rafael Bridge almost caused the loss of the steel span.

Dolphins and Protective Cells Another type of independent structural protective device is that of dolphins or cells, placed so as to intercept a potentially colliding ship. These may be formed of steel sheet

piles, filled with sand and capped with concrete, and given marginal protection against low-energy collisions by timber fendering.

Sheet pile cells, when ruptured by ship collisions, tend to rip and burst completely but have been successful in stopping a 35,000 DWT tanker in Philadelphia (Ostenfeld, 1965) and a 45,000 DWT tanker at the Outerbridge Crossing, New York (Hahn and Rama, 1982).

A more favorable form of cell is the concrete caisson, with multi-directional reinforcing, designed to experience punching shear locally without full failure. Steel cylinder shells can be suitably strengthened to prevent ripping and progressive collapse.

Such dolphins (cells) yield to the impact force by sliding and tilting. In softer soils, the cells may have to be pile-supported and may resemble smaller bridge piers.

The dolphins proposed for the Zarate-Brazo Largo bridges in Argentina (Figure 10) consist of concrete caissons on piles with projecting fender-protected concrete platforms.

Moored Pontoons A number of cleverly designed floating barriers have been developed that fail progressively, thereby engaging adjoining units. The force is ultimately transferred to the seafloor by cables and anchors.

Moored pontoons may be designed as box beams and arranged in sawtooth fashion to deflect the bow of a vessel, or may be arranged as successive beams.

These systems must be designed to resist tidal currents and storm waves and still remain effective. They require maintenance and after each incident, of course, repair. Moored pontoon systems may interfere with the operation of small vessels. They appear to have serious limitations and questionable applicability to the protection of major bridge piers against very large vessels.

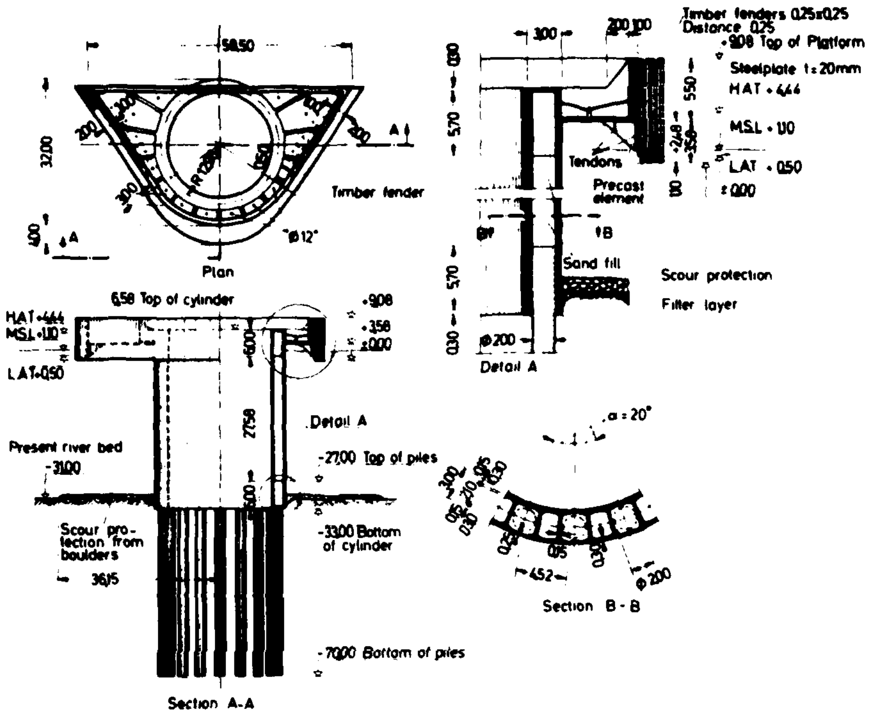
Fenders

A detailed review of fender systems can be found in Derucher and Heins (1979). Fenders are designed to absorb the energy of small and moderate collisions and to reduce the force transmitted to the pier. Ideally, the reaction will be largely nonelastic (to dissipate energy rather than store it); otherwise, a ship hitting a pier on one side may be thrown with greater impact against the opposite pier.

Timber fenders (using both piles and timbers) are designed with multiple elements arranged to bend and deflect, and ultimately to fail in horizontal shear and crush. Rubber fender units are designed to deform by bending, shearing, or buckling, thus maintaining a relatively constant force through a substantial deformation. Steel fender units are designed to fold like an accordion when their elastic strength is exceeded, or to fail in controlled buckling.

Massive concrete blocks may be supported on the basic concrete pier to slide under heavy impact, with the resisting force provided by friction. They may have rubber or other buffers to cushion their final impact on the pier. Large concrete masses have been hung from pile supports in such a way as to swing upward in collision.

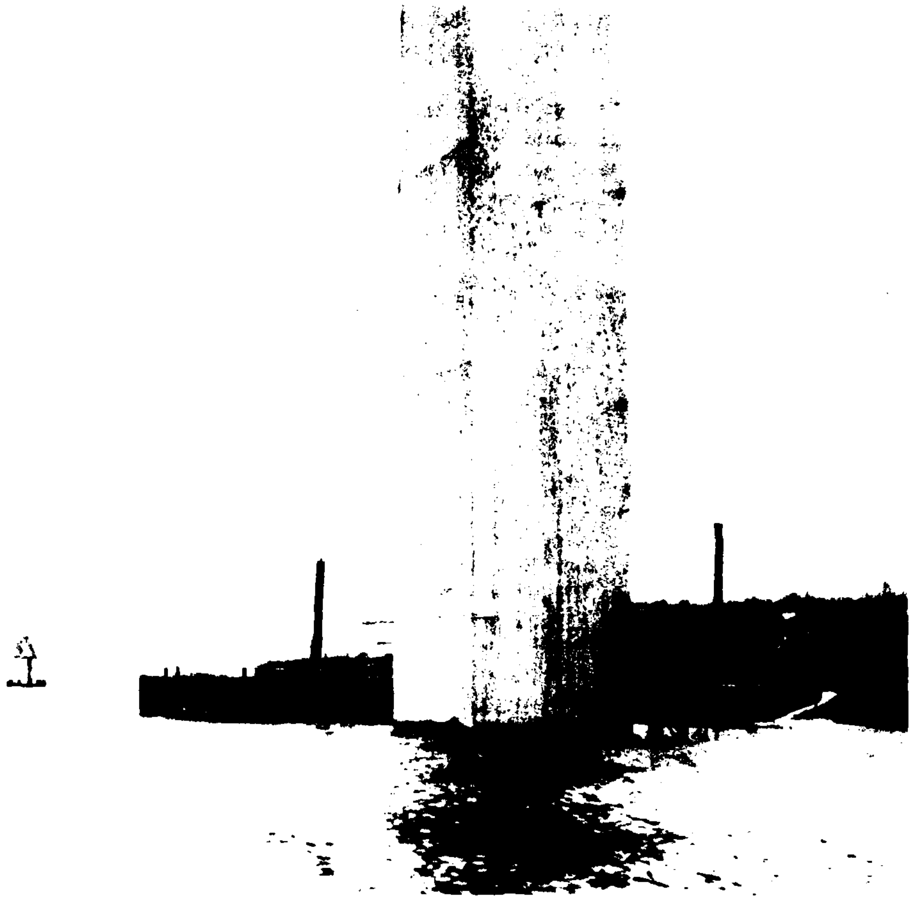
Figure 10 Dolphins proposed for Zarate-Brazo Largo River bridges, Argentina*



*SOURCE: R. Saul and H. Svensson (1982), "Means of Reducing the Consequences of Ship Collisions with Bridges and Offshore Structures," IABSE Colloquium, Introductory Report, p. 175.

Hydraulic dampers have been used on offshore terminals to accept overloads with controlled force and relatively large deformation. They are expensive and difficult to repair; however, the travel (allowable deformation) at high force may be larger than that available with other systems.

Integral fender systems are generally well designed to resist impacts of the small and moderate collisions typical of normal operations. Because their total travel is limited to a few feet, their ability to absorb large amounts of energy, as, for example, in the direct collision of a major ship, is severely limited.



Unprotected pier (in 8 ft of water) of new highway bridge over Houston Ship Channel

Photograph: John Herbich, Texas A&M University

PREVENTIVE SYSTEMS

Analysis

Many evaluations of ship accidents in restricted waterways (for example, Zeitlin, 1975; Maritime Transportation Research Board, 1976, 1981) have shown that the major causes and contributing factors may be characterized systematically as follows:

SHIPBOARD (Navigational/Maneuvering Systems)

- o Human factors (pilot, master, operator)
  - inattention
  - inadequate training or experience
  - communications failure
  - inadequate information
  - physical factors--fatigue, poor eyesight, effects of alcohol or drugs
  - anxiety/fear arising from unusual conditions such as weather, instrumentation or other failures, unexpected maneuvering situation, inadequate information
  - navigational uncertainty (respecting position, orientation, or guidance)
- o Onboard navigational aids (inadequacies, failures)
- o Engine and steering system
- o Vessel controllability (inherent)

EXTERNAL (Navigational/Maneuvering Scenario)

- o Waterway
- o Traffic
- o Aids to navigation

ENVIRONMENTAL (Weather/Hydrography)

- o Visibility
- o Wind
- o Stormy conditions
- o Currents

This systematic characterization can be illustrated in a flowchart (Figure 11) to focus attention on the sources and availability of information for safe navigation, and the use of that information by the pilot in decision making. The U.S. Coast Guard has recently used this approach to evaluate existing systems of aids to navigation (AN) and proposed improvements (U.S. Coast Guard, 1977). Note that the evaluation methodology is shown inside the dotted lines as a feedback loop to provide information about needed improvements.

A similar characterization can be made of the factors critical to reducing the risks of navigating vessels near or under bridges:

SHIPBOARD

- Pilot and master qualifications, training, experience
- Onboard navigational aids
- Inspection and maintenance of onboard instrumentation, communications, navigational and critical engineering equipment

EXTERNAL

- Bridge and waterway design factors
- Traffic engineering measures
- Aids-to-navigation design and maintenance

ENVIRONMENTAL

- Collection, transmission, and presentation of critical information concerning weather, hydrography, etc.

Research studies and assessments have been made of various factors that suggest lines of improvement. Some of these are reviewed in succeeding sections.

Shipboard System

Qualifications of Operators

In the past 10 years, the National Transportation Safety Board (1981b) has made several recommendations addressing the human factors of risk in marine accidents. The recommendations can be grouped in two categories:

- Increasing the qualifications for various classes of mariners; requiring special training, refresher training, and recertification; and
- Strengthening enforcement.

In the first category, it has been noted (General Accounting Office, 1979) that practical demonstrations of professional competence are not required for licenses or renewals issued by the U.S. Coast Guard and that no performance standards or criteria are applied in licensing. Nevertheless, most ships visiting the coastal ports of the United States are of foreign registry. The U.S. Coast Guard is active in international efforts to establish basic standards for vessels, crew qualifications, and equipment.

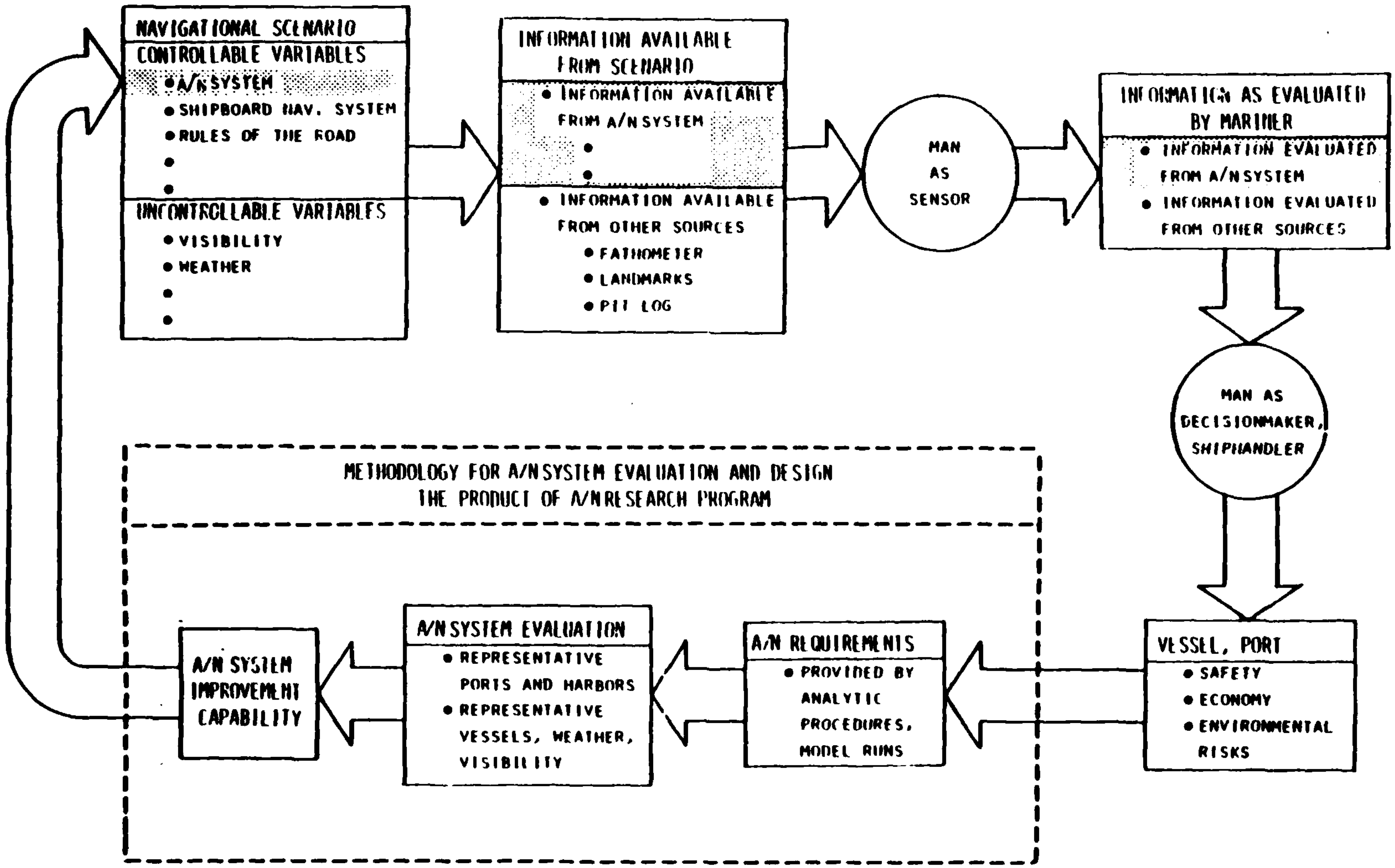


Figure 11 | The process of navigating restricted waterways

As a result of these international efforts, there is now an International Convention on Standards of Training, Certification, and Watchkeeping (International Maritime Organization, 1978). Little attention, however, has been given to training for emergencies. This is an area that might usefully be served by the number of ship simulators in the United States. According to Friedberg (1979), "The most important feature of the simulator is its unique ability to simulate extreme maritime situations in complete safety." The situation arising in reality is an unforgiving teacher.

Shipboard Equipment

In most U.S. harbors, pilots are responsible for safe navigation of ships to and from the seaward approach and protected waters. This requirement ensures familiarity of the ship handler with local, sometimes rapidly changing conditions. Fujii et al. (1974) found, for example, the probability of grounding on a shoal in Uraja Strait to be 2.0×10^{-4} for foreign ships, but 1.0×10^{-4} for Japanese ships, as the location of the shoal was well known locally. Under some conditions and in some harbors, familiarity is not enough; up-to-the-minute information is needed. For example, in the Port of Corpus Christi, Texas, a lift bridge sometimes failed to function. The establishment of a VHF radio link between the bridge and transiting ships helped avert collisions.

Radio links between vessels and bridges can supply the immediate information needed by pilots and bridge operators. Several other kinds of information systems may be helpful.

The official system for radiolocation in the coastal and offshore waters of the United States is loran-C (adopted in 1974), a system of 50 transmitters broadcasting radiofrequency signals to an accuracy of 50 nanoseconds. Position fixing is accomplished by conversion from the observed (hyperbolic) time differences between two or more stations' transmissions to longitude and latitude using charted lines of position supplied by the U.S. Coast Guard. The lines of position are predicted, rather than actual, and the system is subject to errors of transmission, propagation, and reception. The long-range capability of loran-C dictated its selection, and the system's accuracy of 1600 ft in 1200 nmi may be adequate for deep water, but more precise systems are needed for restricted waterways.

A system based on loran-C permits position fixing to an accuracy of 15 ft, provided that

- Loran-C signal quality is at prescribed level and the three available chains are properly oriented geographically (additional chains may have to be established in certain port areas);
- A comprehensive survey of the entire port area is accomplished to provide adequate calibration; and
- An area monitor is situated in the port area to eliminate any drifts in the loran-C signal subsequent to calibration.

Navigation by loran-C to this level of accuracy has been successfully demonstrated (Montonye, 1982; Tideland Signal Corp., 1982). Position fixing can be much enhanced (assuming a calibrated grid) by minicomputers programmed to give continuously updated positions of the vessel and (with additional input data) position in the channel, vessel speed, and distance (or estimated time) to selected waypoints (Roeber and Bradley, 1981; Navigation Sciences, Inc., 1982).

Accurate position-finding systems for particular navigational channels and ports may also be based on a multiple-ranging principle, using strategically placed short-range transponders (American Institute of Aeronautics and Astronautics, 1981) or using a global satellite system.

As with any new navigational aid, the danger exists of over-reliance on one system (new or old) to the exclusion of others (including looking out the window). Kemp (1980) reports preliminary results of ongoing studies that navigators tend to think of position lines from various aids as being right or wrong, rather than as subject to varying degrees of error, and that when given several aids, 65 percent of those tested use only one to estimate position. The introduction of any new system needs to be accompanied by an understanding of its limitations, and training in its use.

External Factors

Location and Appearance of Bridge in the Waterway

For safe vessel navigation, it is desirable that the least maneuverable vessels have an adequate distance of straight channel approach to the bridge from either direction to allow "shaping up" for safe passage. Depending on vessel maneuvering characteristics, and likely currents and winds, this "shaping up" distance can be several miles.

Symmetry of the bridge structure with respect to the channel is of great assistance in "shaping up" for passage. The bridge should be designed to cross the channel at right angles, and should be as level as possible to avoid presenting a confusing aspect, as for example, the 45° angle to the Duwamish West Waterway of the West Spokane Street Bridge in Seattle. The angle can be very disorienting to the pilot who must align his ship precisely to proceed safely under this narrow bridge.

Bridge Markings

Bridge designs that provide several distinguishable lateral structural features, markings on either side of the channel centerline, and unique marking of the centerline location, all constitute visual aids to navigation. Structural features with appropriately unique markings and lights are to be preferred, since these will be useful both visually and by radar. These markings enable pilots (especially when guiding

larger ships) to determine position and maneuver the vessel with respect to channel boundaries, bridge piers, effects of wind and currents, and other vessel traffic.

Marine Traffic Engineering

Rowe (1982), in examining risks of ship-bridge collision, concludes, "The most risk reduction...may be provisions for operational control of traffic during times when margins of safety either for vessels, cargoes, or the bridge-channel system are lacking."

Traffic engineering measures should be considered, developed, and proposed for evaluation when appropriate to assist in the safe and orderly transit of marine traffic under and near bridges. The following possibilities can be useful individually or in combination:

- Traffic separation schemes may be helpful if two-way traffic is heavy and the total channel width allows adequate traffic-lane widths, particularly in turns and bends. Aids to navigation must be planned to facilitate the traffic flow in the desired lanes even in adverse weather. Large, highly visible navigational buoys, possibly equipped with racons or other enhancements, can provide the proper assistance at critical turns, such as the bridge approach turn, to make traffic lanes effective. Mid-channel buoys can also be of use.
- Vessel traffic services such as those provided by the U.S. Coast Guard in a few ports, can help assure orderly flow of traffic in critically congested areas, such as bridge approaches. Such vessel traffic services need not be controlled by a regulatory authority, such as the Coast Guard. Decisions should follow the careful consideration of alternatives by all interested parties--local pilots, harbor and port authorities, ship operators, and others--to ensure that workable systems and rules can be set up, agreed to, and put in operation.
- Other traffic engineering protocols can be worked out to fit local situations, ranging from the installation of traffic lights near critical bends to unique communications requirements for ship-to-ship maneuvering agreements. It is again important that all interested parties work together to develop practical solutions.
- Auxiliary channels are a method of separating traffic, usually by draft. The heaviest traffic may be of smaller, lighter vessels of lesser draft: these can be required to use auxiliary channels rather than the center deep-draft channel. The objective is to reduce the number of meeting and crossing situations.

Aids to Navigation

Aids-to-navigation (AN) systems should be designed to provide proper levels of orientation, guidance, and accuracy in most weather conditions. The aids should be sufficiently redundant to provide the navigational checks necessary for positional certainty in all likely weather conditions (Montonye, 1982). Radar and electronic aids should

be designed to provide orientation and guidance information similar to that provided by visual aids. Positional accuracy, especially cross-track accuracy, should meet the navigational accuracy needs determined by the AN Planning Process (U.S. Coast Guard, 1982) for each type of aid that may be used independently.

The visual aids most useful in approaching a bridge and shaping up for transit are

- Bridge structure and lights;
- Buoys;
- Ranges;
- Fixed beacons; and
- Prominent landmarks (AN of opportunity).

Passage through a bridge is frequently at the most constricted portion of the channel, and the bridge structure as a channel boundary is less forgiving than many shoals. Bridges are all too frequently located at or near bends in the channel, further complicating the navigational and maneuvering situations. Furthermore, rarely is the bridge location, pier and superstructure, visual appearance, and lighting designed systematically for optimal assistance. Yet the bridge itself can be the most effective navigational aid in preventing ship-bridge collisions.

The margins for vessel clearance are drastically reduced for larger vessels when crosscurrents and high winds prevail. The vessel must be steered with a large crab angle (yawed) to maintain a proper vessel track along the channel. Determination of the proper crab angle is itself a difficult problem, and the pilot is generally given little room and imprecise tools to solve it. The determination is particularly critical when the bridge piers narrow the channel's width underneath the bridge. The position of each ship's bridge in relation to its pivotal point for turning is very nearly unique. It is therefore imperative that aids to navigation be placed so that pilots of larger ships can accurately determine not only the ship's position but that of all vessel extremities in relation to the channel--and to the sometimes narrower channel boundaries at the bridge--in sufficient time to shape up safely.

Specific needs for information and its accuracy should be determined by application of the AN Planning Process (U.S. Coast Guard, 1982). In some cases, the required accuracy may be 10 ft to 15 ft, from two or three miles distant in either direction, all the way through the bridge. Most buoys cannot meet this requirement because of positioning inaccuracies and large watch circles. Buoys may be invaluable in bends and turns, however, and many bridges are near bends or turns. If structural features of the bridge, the channel centerline, and specific distances from the centerline are uniquely marked and lighted on the bridge, a reasonable amount of guidance for maneuvering can be provided, but not necessarily the needed level of accuracy. Ranges are the one visual aid that can provide such accuracy if properly designed. Each of the aids to navigation that may be considered for inclusion in the system is briefly described in the succeeding subsections.

Buoys Experiments to determine how piloting performance is affected by the placement of aids to navigation in shipping channels have shown that (Smith and Bertsche, 1980; Bertsche and Cook, 1980)

- o Gated buoys result in better performance than staggered buoys;
- o Spacing of 5/8 nmi between buoys results in better performance than 1-1/4 nmi spacing; and
- o Three buoys in a turn result in a more controlled pullout than one buoy, for both cutoff and noncutoff turns.

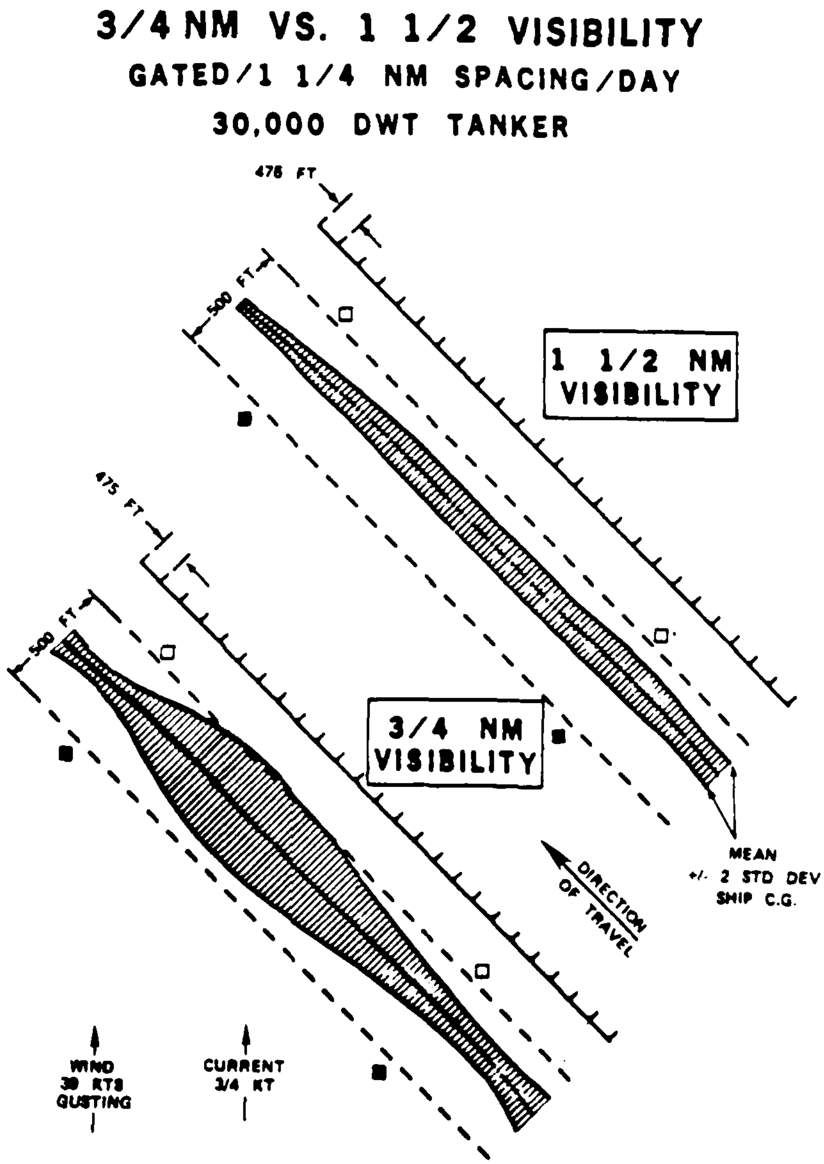
Figures 12 and 13 illustrate the differences in performance observed in simulated shiphandling with different spacing of buoys and in turns with one versus three buoys. The assumption of a 3/4 knot current and a single buoy in Figure 13 allows sufficient uncertainty that some transits leave the channel, but with three buoys, determination of position is sufficiently accurate to keep all transits within the channel. Relative to the difficulties mentioned (Chapter 6, "Considerations of Ships and Waterways") with maneuvering noncutoff turns, properly placed aids to navigation can compensate for the noncutoff turn where additional dredging to reshape the turn is not possible or attended by delays. It has also been found (Smith and Bertsche, 1980) that even the relatively easier cutoff turns can be made much safer by marking the apexes with three buoys, as shown in Figure 14. Failure to mark the two inside apexes results in a tendency to cut the unmarked corner.

Buoys can provide adequate crosstrack positioning accuracy for most bridge approaches, provided they are properly designed and positioned. In far too many instances, buoys are underspecified for the navigational needs they are placed to meet. Where crosstrack positioning accuracies of less than 50 ft are desired, taut watch-circle buoys (having a watch circle of about 30 ft) or Saurus Towers (articulated columns) should be specified. In addition, two pairs of gated buoys should be visible approximately 90 percent of the time (as determined from meteorological observations) ahead of a vessel to allow reasonable crosstrack accuracy using visual buoy alignment. Such a requirement implies larger buoys, brighter lights (possibly sequentially timed so that two ahead may be seen at the same time), and larger daymarks, to permit safe visual approach to narrow passages through bridges. In most cases, existing buoys have watch circles that are too large, and their positioning is not sufficiently accurate. In addition, the buoys and daymarks are too small and their lighting intensity and characteristics are inadequate for precise visual navigation.

Larger navigational buoys may be deployed advantageously at critical channel turns for visual and radar guidance and warning. Radar reflectors installed on such buoys will provide further warning of required future course changes.

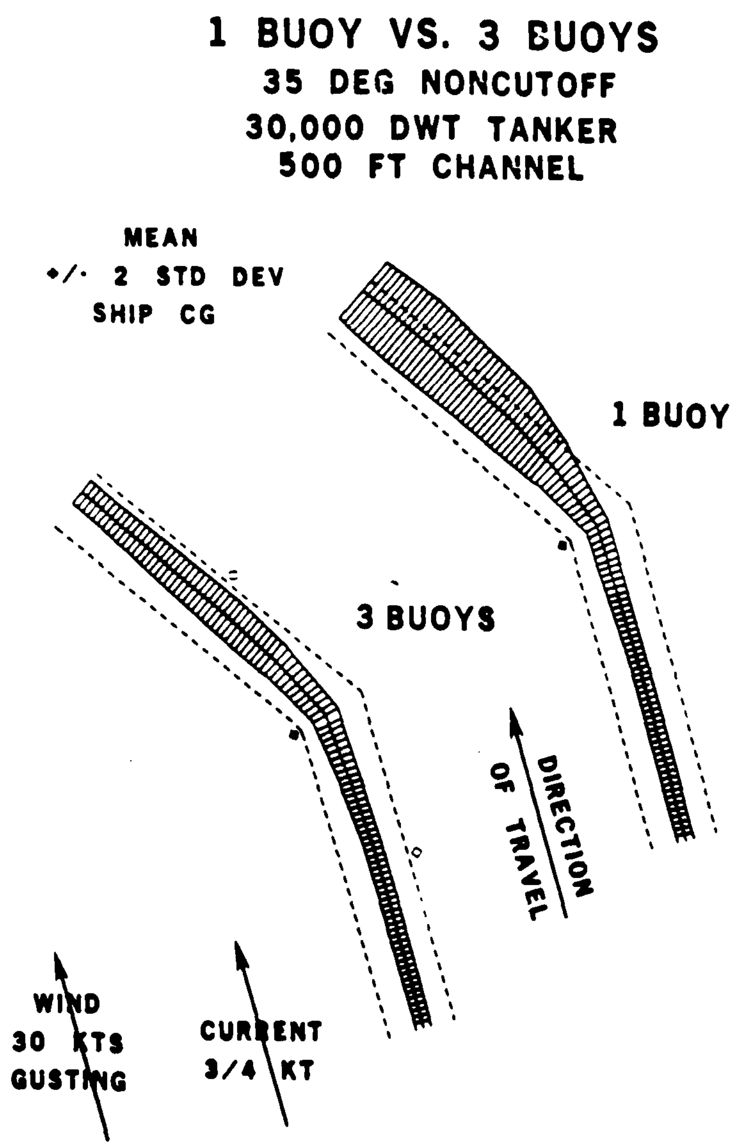
Fixed beacons or sector lights (or both) can be usefully integrated into the design of aids to navigation for bridge approaches because they can provide precise marking of critical alongtrack locations, such as turn points.

Figure 12 Navigational performance for gated buoys spaced 3/4 nautical mile apart and 1-1/2 nautical miles apart*



*SOURCE: William R. Bertsche and Roger C. Cook (1980), "A Systematic Approach for Evaluation of Port Development and Operations Problems Utilizing Real Time Simulation," CAORF Port Studies, Presentations made at the *Fourth Annual CAORF Symposium*, Kings Point, New York, September 29-30, 1980 (Kings Point, N.Y.: National Maritime Research Center).

Figure 13 Navigational performance for 1 buoy marking turn versus 3 buoys marking turn*



*SOURCE: William R. Bertsche and Roger C. Cook (1980), "A Systematic Approach..."

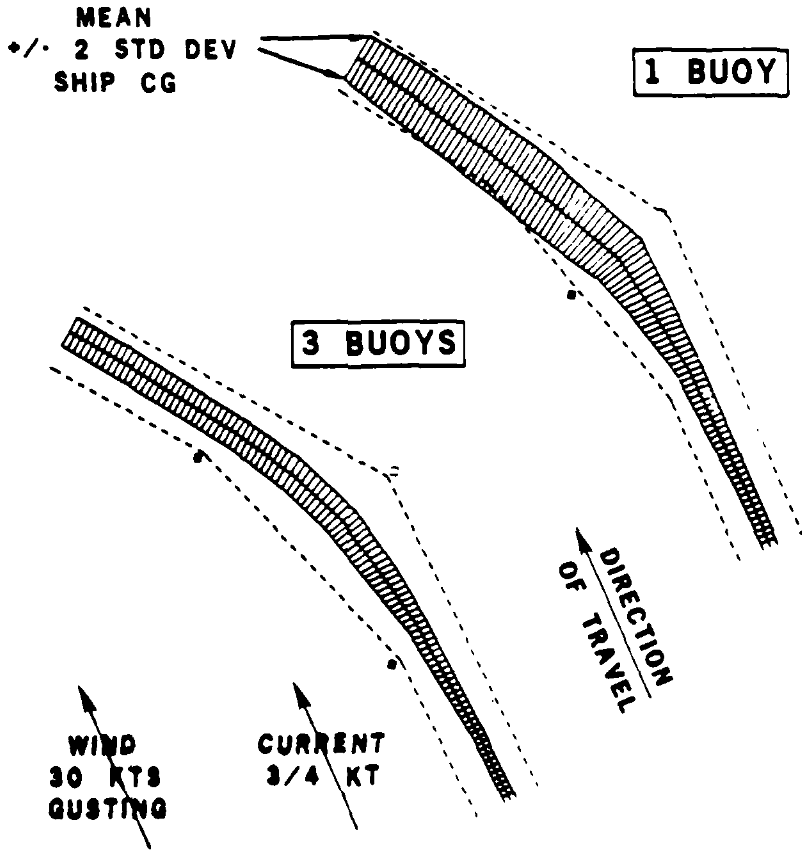
Figure 14 Navigational performance for 1 versus 3 buoys in cutoff turn*

1 BUOY VS. 3 BUOYS

35 DEG CUTOFF

30,000 DWT TANKER

500 FT CHANNEL



*SOURCE: William R. Bertsche and Roger C. Cook (1980), "A Systematic Approach..."

<u>Ranges</u> In the simplest application, ranges are two fixed structures placed in alignment and marked so they provide an accurate indication (when aligned visually) of the desired vessel track along a channel centerline. Ranges may also be used to mark channel boundaries or danger bearings. Generally, the structures are positioned at a distance, usually onshore, away from the end of the particular channel, marked by distinctively visible dayboards, and well lighted by night so that both are clearly visible within the desired channel segment. The rear structure is positioned and constructed so that it may be seen distinctly by ship handlers (without blur) above the front structure.

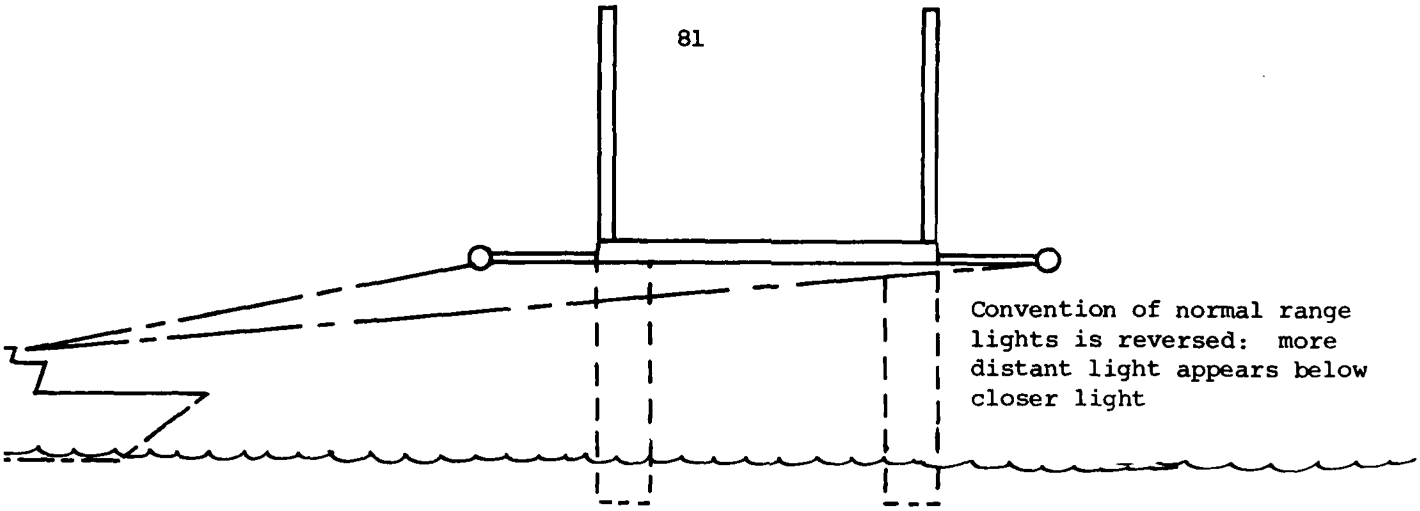
With some adaptation, multiple ranges for vessel navigation could be integrated with bridge design as part of the structure. For unique identification, the bridge channel centerline range could be lighted, green; danger ranges at each edge of the channel, red; and two midpoint demarcation ranges, white. To solve the problem of possible visual obstruction by the bridge's superstructure, the ranges could be mounted on the underside of the bridge. The convention of the rear range's light being observed above the front range's light would be reversed in this case. Some preliminary design work shows that multiple bridge ranges would provide the required accuracy, provided that adequate horizontal separation between the two paired lights can be accommodated. In some cases, this distance might be as great as 100 ft. Spars could be designed to extend these lights beyond the design width of the bridge structure and hinged to allow periodic lamp replacement.

Figure 15 provides both a cross-sectional view and a perspective elevation view (from the vessel on channel centerline) of the basic geometry.

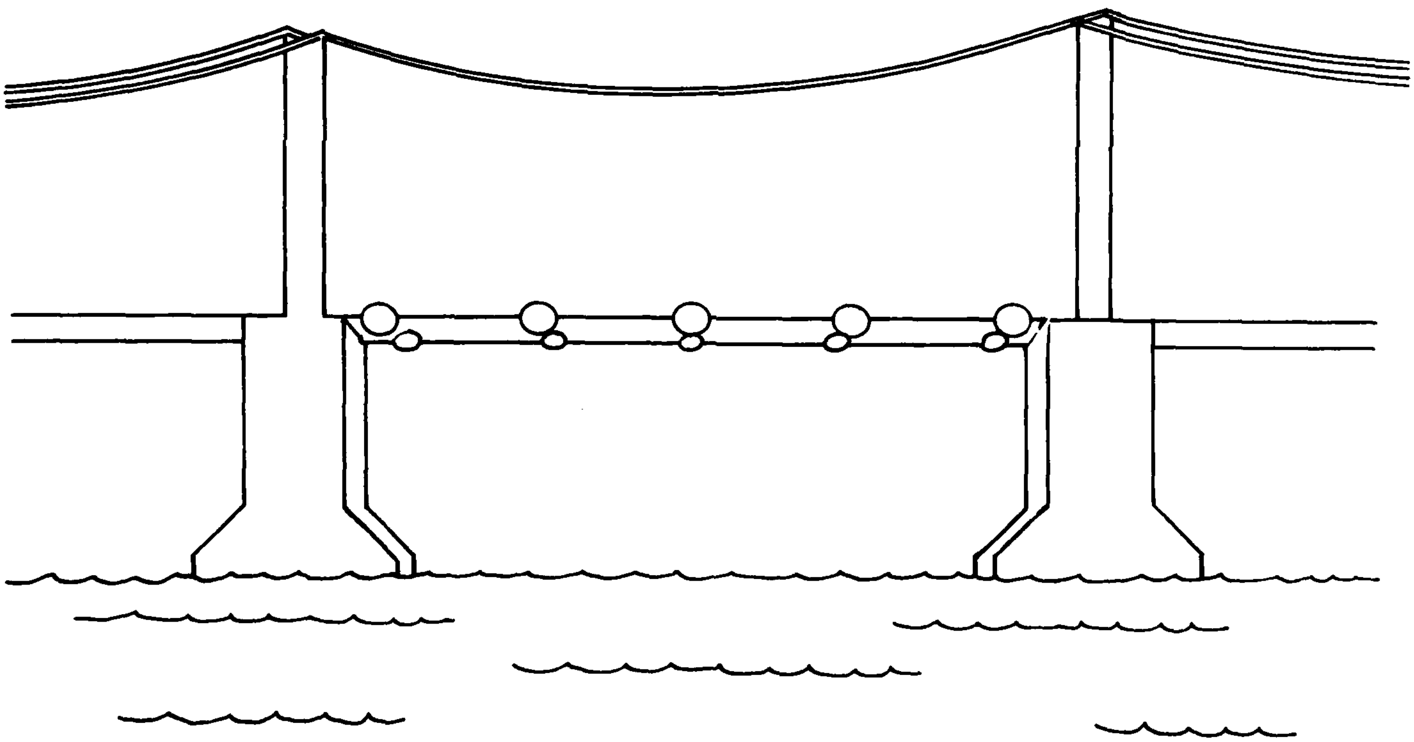
Although these multiple bridge ranges may constitute a unique answer in good visibility to the special navigational needs of transiting certain bridges, they provide no help when visibility is restricted.

<u>Racons</u> Properly designed racons can be mounted on bridges and other approach obstructions. Montonye (1982) and Atkinson (1982) describe the use of such racon aids to determine position accurately and to steer accurately along channel segments. Learning the techniques of steering a channel using a properly designed racon is valuable, particularly for reduced visibility. Racons mounted at the centerline of bridges can provide a very useful adjunct to the bridge ranges proposed here. In the best weather, their use would provide a valuable check on visual navigation, and in foggy or hazy conditions, racon cursor piloting could be the most effective alternative. It is potentially the most accurate radar tool, although it cannot generally provide the accuracies of 10 ft to 20 ft required by some bridge-transiting situations. These situations--heavy fogs or storms, for example--may be better handled by marine traffic management. The advantages of using racons are

- o Assistance in initial approach and shaping up for safe passage through bridges;



Bridge-mounted range lights provide cross-channel navigational accuracy by vertically aligning these lights at distances sufficient to allow large vessels to "shape up" for transiting bridge



Multiple range lights, uniquely identified, allow precise and unambiguous cross-channel positioning of large vessels--by visual navigation--at distances sufficient to allow large vessels to "shape up" for transiting bridge

Figure 15 Illustration of the design and use of multiple range lights on bridges for precise cross-channel positioning of vessels

o Accuracies of 25 ft to 50 ft, if the racon is properly instrumented and adjusted and if the radar reception and presentation are compatible;

o Convenience in restricted visibility, owing to appearance on the radar picture, and use of radar cursor for "course cursor piloting" (Montonye, 1982); and

o Usefulness in (1) improving radar navigation, especially in narrow channels, such as for bridge approaches, (2) substituting for visual navigation in poor visibility, particularly since its use is analogous to the use of a range for visual navigation, and (3) supplementing visual aids during good visibility.

The greatest disadvantage of racons is that they are degraded in heavy rains or thunderstorms. In considering the design of racons for a navigational system, care must be taken to avoid installing too many, since this will lead to ambiguous clutter on the radar screen.

Environmental Factors

Certain information about the physical environment is critical to the judgments involved in piloting. The gathering and communicating of such information is divided among several agencies and local or regional authorities. Nautical charts provide detailed information but are updated only yearly or less frequently and do not reflect short-term changes in locations of buoys or sedimentation. The National Ocean Survey annually publishes tables of daily predictions of tides and currents that permit sufficiently accurate calculations for some areas but not for others. Pilots rely on the Notice to Mariners broadcast by the U.S. Coast Guard at particular times of the day for local conditions.

Lack of accurate, timely information about water depths throughout a port area, water speed and direction, waves, wind speed and direction, and the speed and direction of currents causes delays in shipping and haphazard guessing about the loading of deep-draft vessels, as well as reduction of the margin of safety in navigational decision making. The National Ocean Survey has recently proposed the Real-Time Navigational System to provide tide, meteorological, current, wave, and nautical chart data on demand (National Ocean Survey, 1982).

Such systems have been in operation in Europe and other countries for some years but are still conceptual in the United States. One has been proposed to accompany harbor and channel improvements in the Port of Galveston, Texas (Tideland Signal Corp., 1982).

Motorist Warning Systems

As noted in the introduction to this report, the greatest loss of life in serious ship-bridge collisions has resulted from the continuation of highway traffic after the span has been severed. Following investigation of the Sunshine Skyway Bridge disaster, the National Transportation Safety Board (1981b) recommended that standards be developed for

the design, performance, and installation of systems to detect highway bridge-span failures and to warn motorists. (Railroad bridges are equipped with automatic, fail-safe mechanical signals that are activated by bridge interruption.) Various motorist warning systems have been considered and studied by the Florida Department of Transportation --for example, detection by radar or laser if a ship is out of the navigational channel, and relay to a monitoring screen that would alert the bridge or toll-facility manager to close the bridge to traffic ("Preventing another Sunshine Skyway Bridge Disaster," 1982).

In the Manual on Uniform Traffic Control Devices (Federal Highway Administration, 1978), specifications are given for signals and gates at movable bridges, and specifications for the features that are considered part of the bridge structure (resistance gates) are set out in the Standard Specifications for Movable Highway Bridges of the American Association of State Transportation and Highway Officials (1982). These may be applicable to motorist warning systems on other bridges, given the necessary adaptation.

Interested engineers proposed gates on bridges spanning waterways in Georgia in 1973 and 1975 (Greneker et al., 1974, 1978) and warning lights at half-mile intervals on the causeway of the Lake Pontchartrain Bridge, Louisiana (Burke et al., 1975). Motorist warning systems were proposed for the Tasman Bridge replacement in Australia (Maunsell and Partners and Brady, 1978).

Greneker et al. (1981) propose an early warning system that would track vessels from the bridge or another location (such as a Vessel Traffic Safety Center) by radar (or alternative system) and relay the information to the ship pilot and bridge operator, or to an automatic motorist warning and restraint system. This system could be integrated with a system of precision navigation (discussed in the preceding section).

Motorist warning systems may be sophisticated or simple, as the specific conditions of particular locations and desired results demand. It must be borne in mind that many highway bridges over navigable waterways are not attended continuously and that systems for automatic display of warning signals to the general public tend to be complex, expensive, and of uncertain reliability for infrequent operation over long periods of time.

ESTIMATION OF RISK AND EVALUATION OF MITIGATING ALTERNATIVES

The decision whether to protect elements of bridges from collision with vessels has been for many years a subjective decision based on intuition and the general understanding that the path of vessels may be aberrant in the vicinity of bridges. It was generally assumed that traffic concentrates within the navigational channel and that the geometric probability of collision is greatest there, diminishing toward land (Larsen, 1982). Therefore, channel piers, which are more substantial for typical long-span structures, were provided with protective systems varying from small fenders to major dolphins or islands. It should be noted that while traffic may be concentrated in the channel, the few occurrences of serious ship-bridge collision (Table 2) indicate that the side piers are more susceptible to catastrophic damage by collision than the main piers.

A logical approach to decision making has recently been developed by a number of analysts; generally, the procedures require estimation of the risks of serious ship-bridge collisions, and of the costs of such collisions, as well as provision of protection for various bridge elements if such protection is determined to be cost-effective.

Risk Estimation and Risk Evaluation

Rowe (1982) makes the useful distinction that "risk estimation" denotes the determination of probabilities that an event or events will occur, and the magnitude of the consequences; "risk evaluation" denotes processes for arriving at an 'acceptable' level of risk and determining how to manage the estimated risks. Risk evaluation, he notes, is by nature subjective and value laden. Risk estimation is sometimes represented as value-free, but in the statistical treatment of rare events must deal with large uncertainties. The value judgments of scientists or other experts may in such cases be substituted for data. "Thus, both processes are subjective in nature to some extent," Rowe concludes, as "the treatment of uncertainties in risk estimation affects how risks are evaluated and vice versa.... The scientist or enquirer making a risk estimate cannot ignore the problems involved in evaluating the risks, nor can the evaluators divorce themselves from an understanding of the limits of risk estimation methods."

Data

For the case of ship-bridge collisions of serious consequence, and indeed, for any rare event, Rowe questions whether historical data can ever suffice for determining probabilities. Frandsen (1982) agrees: "Collision probabilities, as such, can of course not be directly extracted from the few cases treated here," he states, referring to his summary of worldwide reports of ship-bridge collisions, taken from many sources.

Single-Cause Analysis versus Multicause Analysis

One aspect of the sources bears mention: marine accident reports are "very informative and reliable," as Frandsen notes, but also "have the goal of placing responsibility among the parties involved in the accident, and not that of establishing bases for future design." Blame is often assigned by a checklist of factors, such as human error, navigational conditions, or mechanical failure. Summations and analyses of such reports have traditionally proceeded by addition to 100 percent. For example, it might be said of some group of marine accidents that 78 percent were caused by human error, 15 percent by mechanical failure, 5 percent by supervisory failure, and 2 percent by "acts of God" or unknown causes. This implies that of every 100 accidents, 83 are caused by human factors, 15 by mechanical failure, and 2 by no known cause. This analysis would focus attention on human error to the unhelpful exclusion of contributory causes.

A thorough, multidisciplinary accident investigation will uncover several causal factors--as many as 25 to 30, all of which contributed to the event. The National Transportation Safety Board (NTSB) conducts such investigations of all aviation accidents and of selected major marine casualties. The results focus attention on the multiple causes, and while it is appropriate to single some out for immediate, and others for intermediate-term and long-term, attention, the results will also (it is to be hoped) point up the occurrence of marine accidents as happening in a system.

As Hooft (1981) states,

> ...when you are not satisfied with the ship-harbor interaction, it will not do--as was common 10 years ago--to blame the dimensions or characteristics of the ships. In the past three or four years, it has become common to cite human error. In another four years, the blame for accidents may fall on the navigational aids! Elements of the system cannot be singled out,....The design is a compromise effected among all the concerns the designer is trying to meet[.]

Estimation of Risk of Ship-Bridge Collisions

Because ship collisions with bridges are rare, uncertainty will accompany any estimation for a particular bridge. A formula devised

for the calculation of collision probabilities must either consider "events of higher probability and smaller consequences whose cause and effect relationships are hypothesized to be similar..., or look at other rare events that have occurred and hypothesize that the same processes are involved as those of concern" (Rowe, 1982). Barratt (1982) concurs: "collisions by passing ships with fixed structures are too rare to allow a reasonable estimate, and so more or less distant analogies have been used."

Similar Events Among these analogies are collisions with light vessels on station, ship-ship collisions, safety-zone or "domain" infringements, and groundings. Analyses of collisions with light vessels and ship-ship collisions indicate that the number of collisions between vessels is proportional to the number of encounters (vessels approaching within some arbitrary distance of one another), and as the number of encounters (in some defined area) is proportional to the square of the shipping density, the number of collisions that can be postulated for an extra vessel or structure is twice the mean number of collisions per vessel (Barratt, 1982). The use of safety-zone infringements as a means to estimate collision frequency is essentially identical to that of shipping density in an area. A "safety zone" of 500 m is stipulated for offshore oil and gas platforms in the United States and the North Sea. "Ship domain" is the area needed around a ship for ease and safety of navigation and is similarly used to estimate collisions as proportional to the number of domain infringements.

Serious questions may be raised about the similarities of the analogues. There are, for example, the differences in sizes between ships or offshore platforms and bridges, the permanence and fixity of bridges, and the navigational objectives and options.

An approach used in risk calculations for various existing and proposed bridges has been to use the models developed from statistical treatments by Fujii et al. (1974) for groundings and by Macduff (1974) for vessel collisions and strandings in the Straits of Dover, and to refine them to make the analogues more nearly analogous.

Fujii et al. find the "probability of mismaneuver," P, by considering the number of strandings, the traffic volume, and the geometrical characteristics of the obstacle (e.g., shoal):

$$P = \frac{Q((D + B)/W)}{N}$$

where

Q = traffic volume;
D = obstacle width;
B = ship beam;
W = waterway width; and
N = number of strandings.

This value was found to vary between 0.6×10^{-4} and 10×10^{-4} in different waterways and to be 1.3×10^{-4} for drilling platforms in the Akashi Strait.

<u>Examples</u> The assessment of ship-collision risks for new or planned bridges is recent and infrequent. Larsen (1982) gives three examples: assessments carried out for the Great Belt (Storebaelt) Bridge in Denmark, the Tasman Bridge in Australia, and the Sunshine Skyway Bridge in the United States.

The Great Belt Bridge model (Frandsen and Langso, 1980) is probabilistic, based on the client's choice of risk level (10,000 years between bridge interruptions). The Tasman Bridge study (Maunsell and Partners and Brady, 1978) uses three approaches: statistical (based on accidents and accompanying information from other bridges thought to be similar), translation of accident data from the Suez Canal to the Derwent River, and estimation based on the models of Fujii et al. and Macduff. The magnitude of risk by the three methods ranged between 10 years and 40 years return period* for serious ship collision.

Two risk assessments were developed for the replacement of the Sunshine Skyway Bridge; both are broadly based on the work of Fujii et al., Macduff, and the probabilistic model developed for the Great Belt Bridge. The first, or preliminary, assessment was developed by COWIconsult, Inc. (1981). This assessment suggested that the probability of failure of a bridge element owing to ship collision be expressed as

$$PO = PA \times PG \times PS \times N$$

where

PO = annual probability of failure of a bridge element;
PA = probability of a vessel's moving aberrantly;
PG = probability of an aberrant vessel's hitting the bridge;
PS = probability that the collision is of high intensity;
N = annual number of passing vessels that are large enough to do serious damage.

Values for these factors were determined separately. The average probability of a vessel's moving aberrantly in a strait is given by Fujii et al. as 2×10^{-4}; the risk assessment for the Sunshine Skyway Bridge used 5×10^{-5}, "due to the use of pilotage and the good marking of the main channels" (COWIconsult, Inc., 1981).

Greiner Engineering Sciences, Inc., also developed a probabilistic assessment of the risks of catastrophic collision for the Sunshine Skyway Bridge, reported by Knott and Bonyun (1983). This approach established categories of assets subject to perils (i.e., collision). Threats were then considered as ordered pairs of the perils and the asset categories. Every threat may be realized in a variety of different ways, each of which is called an event. The analysis involved separate events in terms of various classes of ships and

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*Or inverse of annual frequency

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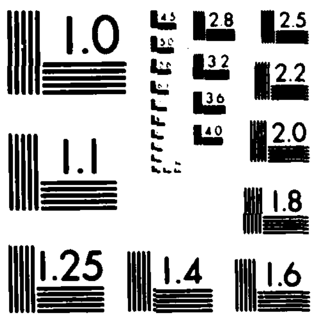


barges based on size. This analysis yielded a potential total of 42 theoretical ship-pier collisions. For each event, event costs (EC) combined the evaluative parameters of the asset group involved. The event costs depend on the severity of the collision.

It is obvious that different levels of severity of ship collisions with bridges can have substantially different costs. For example, a 100,000 DWT ship will cause significantly more damage than a 10,000 DWT ship, all else being equal. The process used for the Sunshine Skyway Bridge evaluation was to allocate by Poisson distribution. This distribution is completely defined once the average severity is specified.

The cost of an event is small until a certain level of severity (critical severity) is realized. That is, once the critical severity is exceeded in a ship-bridge collision, the structure is destroyed with a substantial increase in the cost of the event (see Figure 16).

For the Sunshine Skyway Bridge, the following function is a typical expression:

$$EC = s \times PC \text{ for } s < CR$$

and

$$EC = s \times [(1.4 \times (PC + SC)) + BC + H] \text{ for } s \geq CR$$

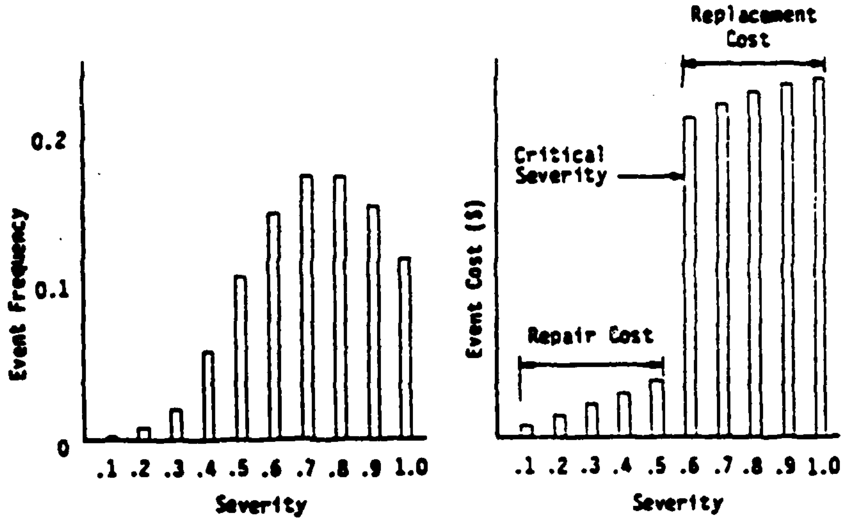
here

EC = event cost;
s = severity;
PC = pier cost;
SC = span cost;
BC = business/commerce cost;
H = loss of human life cost;
CR = critical severity.

The BC costs would include the cost of interruption of motorist or railroad travel across the bridge, the costs to the users of the port if the channel were blocked by ship or bridge wreckage, the cost of damage to the vessel, and the cost of damage to the environment. The factor '1.4' is included to account for the higher cost of replacing the pier and span than their initial construction cost. An event cost must be developed for each asset category and for the variety of events affecting each asset category.

For each event described, an exposure can be calculated. Exposure may be defined as the expected value of loss of assets as a result of the event (expressed usually as dollars per year). Traditionally, exposure is derived by multiplying an event cost by its frequency. This is not entirely satisfactory, since an event might have a wide variety of associated costs depending on external circumstances. These circumstances may be lumped together to yield a range of costs distributed against the severity of the event as defined here. The event exposure is calculated by multiplying the annual frequency of an event of any severity by the expected cost per event. The expected cost per event can be generated using statistical techniques. In fact,

Figure 16 Representative frequency-severity-cost function relationship



$$EX = AF \times \sum_{s} [EC(s) \times P(AS,s)]$$

where AS is average severity.

In the second Sunshine Skyway study, the annual frequency of vessel collisions was estimated for each event category using the following equations:

$$AF = N \times PA \times PZ \times PG \times PE$$

and

$$AFC = AF \times PC$$

where

- AF = annual frequency of a ship collision with a bridge component;
- AFC = annual frequency of bridge component collapse due to ship impact;
- N = number of ships and barges in the various vessel categories which have the potential to strike a particular bridge element;
- PA = probability that a vessel is aberrant (out of the channel);
- PZ = probability that an aberrant vessel is located in a zone in front of a particular pier or pier grouping;
- PG = geometrical probability that a vessel strikes a bridge component;
- PE = probability that the vessel master or pilot has not taken successful evasive action to avoid the collision;
- PC = probability of total collapse.

An advantage of this procedure is that the costs of the events and the exposure costs of groups of assets can be used to compare the costs of protective alternatives against their benefits (reductions of exposure costs). This is briefly described in a succeeding section.

Other Possibilities for Risk Assessment

Redundancy and Safety Margins

Rowe (1982) suggests that "safety is a function of multiple, redundant systems, each with a margin for error intrinsic to the system. Moreover, accidents only occur when the margin of error in each of the redundant systems is overcome simultaneously for whatever reasons." The difference between a collision and a near miss is merely whether a margin of distance exists.

"As long as margins of error (or safety) are not exceeded," Rowe continues, "accidents do not occur. What is not known is how much margin of error and redundancy exists and whether these margins are being reduced." In a study of casualties in the Houston-Galveston, Texas, area (Thompson et al., 1981), the U.S. Coast Guard found that over the period 1969-1977, commerce increased 100 percent but transits only 15 percent, as larger ships achieved dominance in the world fleet. The number of casualties rose during this period, despite the small increase in vessel traffic and suddenly accelerated with the occurrence of 22 accidents in a six month period. The study concludes that the system is saturated and that safety can be expected to continue to deteriorate.

Rowe warns, "Once capacity [of redundant systems] is exceeded, all margins for error may disappear and a steep rise in collisions and rammings may be expected. The change in hazard potential is abrupt and nonlinear, [and] impending conditions may well be masked up to the point of exhaustion."

Vulnerability Assessment, and Hazards and Risk Analysis

Some preliminary attempts have been made to assess the vulnerability of various parts of bridges and of ships to various modes of failure and to determine system vulnerabilities. For bridges (except in the cases cited), these attempts have consisted of engineering design reviews or failure mode and effects analysis of particular components (particularly if a similar component has failed in a bridge elsewhere). For ships and waterways, full-scale trials, model tests, and simulations have been conducted to gain understanding of inherent or piloted ship controllability and the limits of waterway navigability. Simulation studies have typically concentrated on one or another aspect of the system (placement of navigational aids, validation of channel design, assessment of navigational difficulty with various ship loadings, evaluation of "man in the loop"). Although in these attempts much information has been collected that could be useful in other applications, insufficient interdisciplinary communication has so far prevented such applications (Marine Board, 1981, 1983).

Fault-tree and event-tree analysis has been used to evaluate the risks of a variety of systems--nuclear power plants, chemical and explosives manufacturing, transportation of hazardous cargoes--and it might usefully be applied to the ship-bridge-waterway system. This type of analysis begins by diagramming the system and the interactions of people with it (and may include the physical environment). Failure modes and failure rates of various components of the system are considered, as well as the further events necessary for serious accidents. Diagramming proceeds by assessing the effects of failures at all points in the system.

The ordered diagrams yield schematic sequences and combinations of events that lead to undesired "top events." Boolean algebra is used to reduce the complex diagrams to their basic elements, and probability

theory is used to evaluate the importance of events and combinations of events that bring about undesired top events (illustrated in Figure 17).

A promising aspect of these analyses is the development of several accident scenarios leading to the same undesired top event--say, collapse of the bridge span. As indicated in the review of ship-bridge accidents, several have involved the superstructures of ships and bridges, yet such accidents have not been addressed in the limited risk analyses that have been undertaken for specific bridges.

Combined Analysis and Comparison of Risk-Reducing Measures

Rowe (1982) suggests that the margins of safety for a ship-bridge-waterway system can be estimated by characterizing the elements of the system and a range of events consequent to faults or errors. This could be carried out by the techniques of fault-tree/event-tree analysis.

An interesting analogue is the "equivalent safety concept" developed by the National Materials Advisory Board (1983) for the relative hazards attending port calls of vessels carrying hazardous cargoes, expanding on the concept introduced by Danahy and Gathy (1973). The methodology is to develop formulas to calculate a separate, dimensionless hazard index for cargo, vessel, and port. The Transportation Safety Index (TSI) is the vessel index divided by the cargo index. TSI is then compared to the port index for a particular port call. While these are quantitative, their use is intended to be comparative and to permit decision making by the Captain of the Port.

Analysis of the factors in the formulas enables the parties to the decision to achieve acceptable safety by a number of corrective or mitigating actions (this is the equivalent safety concept).

Two advantages of these methods, were they to be applied to prevention and mitigation of ship-bridge collisions, are that they (1) focus explicit attention on factors of the system that might otherwise escape notice and (2) suggest an array of corrective actions that might be taken. The value of the second advantage is heightened by the number of parties responsible for taking these actions.

Cost-Effectiveness Analysis

A cost-effectiveness analysis of various protective measures for the Sunshine Skyway Bridge replacement was conducted by Greiner Engineering Sciences, Inc. (Knott and Bonyun, 1983). The costs of events and the exposure costs of groups of assets having been established (as described under "Examples" in the section "Estimating of Risk of Ship-Bridge Collisions"), studies can be undertaken of protective alternatives such as dolphins, artificial islands, navigation improvements, electronic navigational aids, and motorist warning systems.

The cost of each protective alternative is the price of its construction, maintenance, and operation. Benefits are represented by

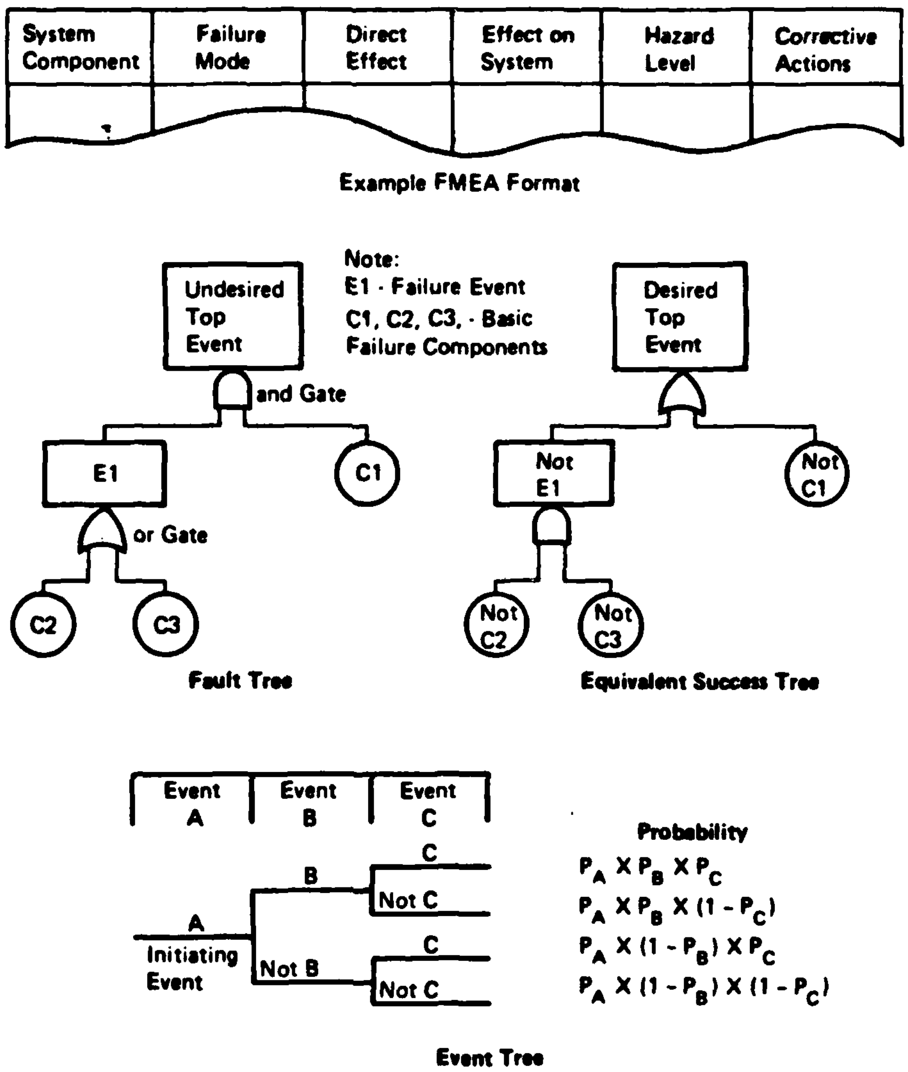


Figure 17 Failure and effects analysis--event-tree and fault-tree diagramming*

*SOURCE: R. Pape, H. Napadensky, and T. Waterman (1980), "Evaluating Hazards of Manufacturing and Handling Pyrotechnic Materials," Proceedings of the Seventh Pyrotechnics Seminar, Vail, Colorado, July 14-18, 1980, pp. 505-528.

any reduction in exposure costs the alternative can be shown to provide. Costs and benefits can be converted to present values by standard discounting procedures, based on assumptions for inflation and interest rates or based on the net values of money. From these present values of costs and benefits, a series of indicators of economic desirability can be derived, including cost-benefit ratio, the present value of net benefits, the internal rate of return on investment, and payback period.

Table 3 presents typical cost-benefit results using this methodology to compare alternatives for bridge-pier protection.

It is interesting to note the great cost-benefit ratio of standard navigational improvements as a pier protection alternative, and the higher ratio of electronic navigational systems to pier-protection. Obviously, preventing the collision is less expensive and more beneficial than mitigating its consequences. Relatively modest expenditures for improved aids to navigation may, as indicated in Chapter 11, "Preventive Systems," alleviate navigation of many otherwise hazardous or difficult portions of a channel or port besides transiting an overwater bridge.

One alternative not included in the table is improvement of the waterway and traffic engineering alternatives, as the costs and benefits are usually decided on different bases--those, for example, of increased ship commerce or decreased shipping and other losses.

In many cases, the owner of the bridge is not the general public. The analytic tools described here might be used in such cases to define the beneficiaries of protective alternatives and to allocate payment of the costs for carrying out the selected alternative(s).

Discussion

The applicability, usefulness, and accuracy of the results obtained from these techniques (or any techniques employing statistical analysis) depend on the quality of information supporting the input assumptions and used as data, and on the experience and ability of the analysts. Not surprisingly, experts differ, even if they use essentially similar techniques. Whatever the methods or techniques employed and judgments made, they should be set out and documented in sufficient detail to be replicated and to provide guidance to the parties and decision makers responsible for various parts of the ship-bridge-waterway system.

It should also be noted that whatever the results of the analysis, some actions may be more expeditiously undertaken than others. The analysis may show, for example, that the benefits of channel improvement per dollar expended are superior to those of alternative bridge designs. Nevertheless, effecting major channel improvements is a lengthy process in the United States--15 years to 25 years (Marine Board, 1983)--and in these circumstances, the addition of pier-protective devices may be dictated by common sense.

Pier Protection Alternative	Initial Cost	Annual Maintenance	Expected Lifetime (Years)	Benefit/Cost Ratio (5% Discount)
Dolphins - 4 Piers	$17,230,000	$23,000	35	3.48
Dolphins - 6 Piers	20,022,000	26,880	35	3.32
Dolphins - 12 Piers	28,603,000	38,400	35	2.26
Islands - 4 Piers	20,440,000	7,000	50	4.59
Islands - 6 Piers	24,080,000	14,000	50	4.33
Islands - 12 Piers	34,240,000	28,000	50	3.54
Standard Navigation Improvements	1,000,000	6,000	20	17.33
Electronic Navigation System	600,000	8,000	10	6.49
Motorist Warning System	220,000	5,000	10	4.26

Table 3 Benefit/cost ratios for pier protection alternatives*

*SOURCE: Michael A. Knott and David Bonyun (1983), "Threat Analysis for Ship Collision against the Sunshine Skyway Bridge," IABSE Colloquium, Preliminary Report, pp. 371-380.

13

LEGISLATIVE AND INSTITUTIONAL FRAMEWORK

In the United States, policies and procedures pertinent to ship-bridge collisions have evolved in response to several concerns. The evolution has taken place within the traditional responsibilities of federal agencies for the protection of the public and of navigation, and, in recent years, for the protection of the marine and coastal environment. The policy setting and decision making processes of these agencies include some set of mechanisms for determining the state of knowledge and technical feasibility regarding specific problems and solutions, and mechanisms for seeking consensus among those who will be required to comply (or who have an interest in the outcome, or both).

Among the traditional areas of responsibility are highway bridge safety, under the auspices of the Federal Highway Administration (FHWA), and navigational safety, under the U.S. Coast Guard (both agencies are in the Department of Transportation), as well as creation, improvement, and maintenance of the waterways, under the U.S. Army Corps of Engineers. Important sources of information about technical feasibility and consensus that these agencies draw on are the professional and engineering organizations.

While the policies and procedures respecting bridges, ship traffic, and waterways evolved separately, recent regulations and directives require consultations with local ship pilots and Coast Guard districts concerning proposed overwater bridges and waterway improvements. The Coast Guard and FHWA have signed a memorandum of understanding allocating responsibilities for the policies and procedures governing bridges over navigable waterways to streamline permit review and avoid duplications. Nevertheless, little or no attention has been given to the mutual concern of ship-bridge collisions.

Much more interdisciplinary and interagency communication is needed to enhance the understanding various specialists have about aspects of the ship-bridge-waterway system other than their own.

Regulatory Authorities and Activities

Ships

As indicated in preceding chapters, the U.S. Coast Guard is responsible for the safety of navigation in the channels and ports of the United

States--including the provision and maintenance of aids to navigation, and the regulation of vessel traffic, particularly of ships bearing hazardous cargoes.

In the late 1960s and early 1970s, worldwide public and official concern was raised about the maneuverability of new, dramatically larger ships and about the possibilities they posed of polluting accidents. The international forum for maritime concerns is the International Maritime Organization (IMO, formerly the Inter-Governmental Maritime Consultative Organization, or IMCO). The U.S. Coast Guard is an active participant in IMO on behalf of the United States. Many actions have resulted from IMO deliberations; among them, agreements by the participating nations to require onboard navigational equipment, to institute traffic separation schemes where indicated, and to revise the rules of the road.

The Port and Waterways Safety Act gave the U.S. Coast Guard authority to enact the international agreements, as well as additional responsibilities to protect the marine and coastal environment. (This new act, as subsequently amended, was itself an amendment of the 1935 Tank Vessel Act, passed in consequence of increased oil shipping and several fatal accidents.) Under these legislative authorities, the Coast Guard can establish, operate, and maintain vessel traffic services and systems, require installation of specified navigational equipment, and control vessel traffic. Amendments to the act in 1978 included an inspection and compliance program, coordinated vessel traffic systems in international waters, and stronger environmental measures. (The act is codified in 33 U.S.C. 1221-1227.)

Another ongoing activity of the U.S. Coast Guard and IMO is cooperative research in the maneuvering characteristics of ships, with a view to developing minimum standards. As a first step, all vessels are required to carry maneuvering information from their sea trials in deep water. This is minimally helpful to ship pilots in restricted waterways, where the maneuvering characteristics are greatly changed, but provides better indication than no maneuvering data at all.

Bridges over Navigable Waterways

Federal authority to regulate bridges over navigable waters originated with the River and Harbor Act of 1899. Bridges determined by the U.S. Army Corps of Engineers to be obstructive had to be removed or altered by the bridge owner. In 1941, the Truman-Hobbs Act (33 U.S.C. 511-524) offered federal financial assistance to the owners of such bridges. Action on these authorities was transferred to the U.S. Coast Guard in 1967.

This action consists of carrying out the Bridge Administration Program (requiring the alteration of obstructive bridges and offering a federal share of the cost) and reviewing the required permit application for new bridges over navigable waterways. The principal concerns of the Coast Guard in permit-application review are protection of the environment and navigability, but pier fenders may be required for approval of bridge-construction permits. The Coast Guard is directed to consult with other federal agencies that have jurisdiction or special expertise in environmental or navigational matters.

Useful action can be and has been taken through these programs: the considerations that enter the decision making process could be extended.

Waterways

The design, construction, improvement, and maintenance of waterways in the nation's ports have been carried out for the past 150 years by the U.S. Army Corps of Engineers. A lengthy, 20-step process has evolved for gaining approval and public funds to create or improve waterways, as these projects must be balanced against other large public-works projects to develop water resources. The United States is now deliberating new arrangements for planning and funding these projects.

While the time required to complete the existing process exceeds the half-life of the world fleet (Marine Board, 1983), individual districts of the Corps have undertaken engineering design studies for authorized projects to test various channel configurations against piloted ship simulations (for example, Williams et al., 1982). A recent regulation (U.S. Army Corps of Engineers, 1981) also requires consultation and agreement from the local U.S. Coast Guard and ship pilots about the design of waterways.

Bridges

In the past 20 years, failures and collapses of older bridges attended by fatalities focused the nation's attention on bridge safety. As a result, Congress established a program of periodic inspections to identify bridge conditions, maintenance needs, and safety problems, and a program of providing funds to the states to help replace unsafe bridges. The programs were initially limited to bridges on the federal-aid highway system; later legislation included other highway bridges. These are briefly reviewed in succeeding subsections.

Standards of design and inspection are developed by the two professional organizations, the American Association of State Highway and Transportation Officials (AASHTO) and the American Railway Engineering Association (AREA). Those of the former are referenced by federal regulation; railroad bridges are all privately owned in the United States.

Replacement and Rehabilitation The Surface Transportation Assistance Act of 1978 (Public Law 95-599) extended and expanded the Special Bridge Replacement Program (initiated in 1970), now retitled the Highway Bridge Replacement and Rehabilitation Program. Rehabilitation rather than complete replacement of unsafe bridges was permitted for the first time, and funding was greatly increased as rehabilitation must be to current standards. The program also includes bridges off the federal-aid system and over highways.

In addition to funds provided through the Surface Transportation Assistance Act, other federal-aid highway funds can be used to replace or rehabilitate federal-aid bridges. States may use federal highway safety funds to install traffic control devices and other safety improvements at bridges.

Deficient highway bridges on all public roads may be eligible for replacement or rehabilitation. Agencies participate in this program by conducting bridge inspections and submitting inventory and appraisal data to the FHWA for an eligibility evaluation. (Policies and procedures for administering the Highway Bridge Replacement and Rehabilitation Program are contained in 23 C.F.R. D-650.)

Inspection Railroad bridges are inspected and maintained to AREA standards by their owners.

The Federal-Aid Highway Act of 1968 established the National Bridge Inspection Program, administered by FHWA (23 C.F.R. C-650). Regulations (Federal Register, May 27, 1971) directed the states to inspect their federal-aid bridges by July 1, 1973, to make an inventory, and to reinspect them at least every two years. The regulations give the inventory data to be maintained on each bridge, inspector qualifications, and inspection methods. The states may use federal-aid highway administration and planning funds for training, inventory, and inspection.

Each state highway department must include a bridge inspection arm capable of performing inspections in accordance with the Manual for Maintenance Inspection of Bridges (American Association of State Highway and Transportation Officials, 1978).

Voluntary Consensus Standards

Consensus standards for the design and inspection of bridges are developed by the professional community through the technical committees of the American Association of State Highway and Transportation Officials (AASHTO) and the American Railway Engineering Association (AREA), circulated to the membership for comment, revised, and submitted for approval to executive committees.

While the standards of both organizations are voluntary, they are (or may be) adopted by reference in federal regulation. Officials of federal agencies participate in the activities of both organizations to stay current with engineering developments.

Design

AASHTO publishes the Bridge Manual (Standard Specifications for Highway Bridges) every four or five years and interim specifications yearly. These are incorporated by reference in federal and state regulations. AASHTO standards and specifications must be met for any highway bridge built or restored with partial federal funding.

Railroad bridges are privately owned in the United States, and virtually all are designed to AREA standards in the AREA Manual for Railroad Engineering. The Federal Railroad Administration (FRA) states regulatory design requirements only for track.

Neither set of standards addresses structural design to resist ship impacts, but AREA added "Pier Protection Systems at Spans over Navigable Streams" (Part 23) to Chapter 8 of the AREA Manual for

Railroad Engineering (American Railway Engineering Association, 1980). This new part addresses dolphins, floating shear booms, hydraulic devices, and fenders.

Inspection

AASHTO Manual for Maintenance Inspection of Bridges and the AREA Manual for Railroad Engineering serve as uniform standards for determining the physical condition and maintenance needs of existing bridges. There are no inspection standards related to ship collisions. Waterway considerations address stream flow and ice, and the adequacy of the waterway opening. One condition that is addressed is scour, which, as indicated in Chapter 9 of this report, "Geotechnical Aspects...," may reduce the resistance of bridge piers to collisions.

Other Regulatory and Institutional Activities

As indicated in Chapter 12, "Estimation of Risk and Evaluation of Mitigating Alternatives," much can be learned from a multicausal, multidisciplinary investigation of accidents, and these are required for marine accidents involving fatalities. In its report on the ramming and collapse of the Sunshine Skyway Bridge, the National Transportation Safety Board (1981b) drew a number of conclusions and made recommendations to the FHWA, U.S. Coast Guard, and state of Florida, among others.

Activities Initiated as a Result of NTSB Report

Federal Highway Administration The FHWA has been evaluating the various factors involved in ship collisions with bridges to reduce their occurrence and severity through corrective action--such as the installation of motorist warning systems (Federal Highway Administration, 1983). The FHWA is continuing to follow through on this and other recommendations of the National Transportation Safety Board (NTSB). A memorandum to regional federal officials and highway engineers (Federal Highway Administration, 1982) emphasizes early coordination with the local district of the U.S. Coast Guard in the design phase of overwater bridges, and recommends that the potential for ship-bridge collisions be considered, "so that cost-effective means can be developed for minimizing such hazards."

U.S. Coast Guard The U.S. Coast Guard has developed simulations of hazardous bridge transits to improve understanding of the interactions involved, and to investigate mitigating actions, and a computer program to assist in the engineering of fendering systems. The system of aids to navigation in Tampa Bay has been redesigned (besides the bridge replacement, the waterway has been deepened). Three buoys now mark the turn closest to the bridge.

State of Florida The Florida state department of transportation (1980) reviewed and compared strategies to protect the replacement Sunshine Skyway Bridge and other overwater bridges in the state, to prevent accidents, and to warn motorists. The state is pursuing further

engineering design studies for the bridge and protective system and may compare them in simulated ship passages using the Computer-Aided Operations Research Facility (CAORF) of the U.S. Maritime Administration.

With a view to improved navigational information, the state legislature enacted a bill requiring licensed state ship pilots to use electronic navigation equipment if it is provided to them.

U.S. Army Corps of Engineers Although not accompanied by a recommendation, a conclusion of the NTSB report states that the turn into one navigational channel from another before the bridge "is too close to the [bridge] to allow safe aborting of a large vessel's inbound voyage when the turn is not properly executed." Deepening of the navigational channels in Tampa Bay had long since been authorized and appropriations had just been made when various agencies and organizations were discussing changes following the Sunshine Skyway disaster. The district Corps of Engineers estimated that widening or straightening the turn would cost an additional $40 million to $60 million. The Coast Guard's Marine Board of Investigation did not recommend changing the turn, reasoning that it would not reduce the risks of similar accidents. The district office of the U.S. Army Corps of Engineers is considering the addition of emergency anchorages for incoming ships.

Forums of Engineering Concerns

All the professional engineering organizations serve to bring problems, innovative solutions, and new developments to the attention of their members. AASHTO and AREA are explicitly committed to encouraging innovation. The Society of Naval Architects and Marine Engineers (SNAME) has worked for many years to keep its members up to date with research results and technical innovations and maintains a technical panel concerned with ship controllability. The American Society of Civil Engineers (ASCE) and International Association for Bridge and Structural Engineering (IABSE) sponsor meetings and publish journals to stimulate and enhance the profession, and to disseminate information. IABSE, it should be noted, has been the leading edge of concern about ship collisions with bridges, having published an analysis in 1965 and several subsequent papers, and convened an international colloquium on ship collisions with bridges and offshore structures (May-June 1983, Copenhagen).

While the activities of professional engineering organizations in the United States have resulted in much useful information and its dissemination within each profession, there is insufficient interdisciplinary communication. The individual professions remain unaware* of the systematic problems posed by overwater bridges and the state of knowledge or technology in other disciplines.

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*An interesting exception is the interest taken by the local chapter of the American Institute of Aeronautics and Astronautics (1981) in applying principles of aircraft navigation to precision ship navigation in Tampa Bay.

Discussion

Several opportunities present themselves for considering ship-bridge collisions within the present regulatory and institutional framework. Voluntary consensus standards can be developed for the design of new overwater bridges and for protective systems in the professional organizations, ship-collision hazards can be included in the inventory of bridges at risk, and aids to navigation and the lighting and marking of bridges can be specified for the waterways underneath the bridges.

These actions would be most useful: they will not by themselves yield the most efficient or complete solutions. These would best be served by systematic risk and hazards analysis that examines the operations and failures of all the parts within the overall system. As much as possible, all first steps taken by interested parties need to be coordinated with others.

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SUMMARY OF COMMITTEE EXPERTISE

Thomas R. Kuesel, Chairman, is chairman of the board of Parsons, Brinckerhoff, Quade and Douglas, Inc., and director of design services for major structural works. His experience encompasses design of 120 bridges and 80 tunnels in 36 states and 22 countries, including several bridges of different types built in marine and coastal locations. Mr. Kuesel is a member of the National Academy of Engineering.

Kenneth N. Derucher, professor of civil engineering at Stevens Institute of Technology, has for several years conducted research, development, and consultative work addressing bridge protective systems; bridge inspection, rating, and rehabilitation; and analysis of ship impacts. Among his technical publications is Bridge and Pier Protective Systems and Devices.

Ben C. Gerwick, Jr., is professor of civil engineering at the University of California, Berkeley, and consulting engineer on the use of concrete in the marine environment; deep foundations; offshore platforms in the North Sea and Arctic; and major overwater bridges worldwide. He is a member of the National Academy of Engineering and past chairman of the Marine Board.

J. Wesley Miller is principal engineer with Spectra Research Systems and vice president of NDE Technology, Inc. He provides systems and safety engineering services to a variety of clients, ranging from marine industries to aerospace facilities. Dr. Miller's experience includes navigational planning for the Galveston Entrance Channels, development of computer planning techniques for aids to navigation, and experimental design for the ship bridge simulator of the Computer-Aided Operations Research Facility (CAORF) at Kings Point, New York.

Pat Neely, Jr., is president of the American Pilots Association. He has been a licensed ship pilot in Houston, Texas, for the past 25 years, following 12 years' progressively responsible sea service in the U.S. Navy and U.S. Merchant Marine. He has served aboard and piloted a formidable number and variety of vessels.

James E. Sawyer is president of Greiner Engineering Sciences, Inc., and the firm's special consultant for bridge projects. He pioneered the use of curved steel girders and welded-steel bascule bridges in Florida and participated in the development of several computer programs used in the design of complex bridges. Mr. Sawyer is past director and

fellow of the American Society of Civil Engineers and chairman of the Commission on Marine/Bridge Safety, formed by the Florida Engineering Society following the destruction of Tampa's Sunshine Skyway Bridge in a disastrous ship collision.

Holger S. Svensson is project manager of the engineering firm Leonhardt, Andrae und Partner in Stuttgart, West Germany, with primary responsibility for all aspects of the design and construction of bridges. He has for many years been concerned about ship collisions with bridges and has published several technical articles in European journals on collision forces and bridge-protective systems. Mr. Svensson was a consultant on the design of the replacement Sunshine Skyway Bridge and protective systems.

William C. Webster is chairman of the Department of Naval Architecture, University of California, Berkeley. Besides advanced vessel design, Dr. Webster's research and development work has principally concentrated on ship maneuverability in collision avoidance; transient-maneuvering testing and equations of maneuvering; and ship interactions with hydrodynamic and other forces.

Appendix: Bridges Spanning Major Coastal Waterways*

*Depths 30' or greater

APPENDIX A:

ATLANTIC SEABOARD BRIDGES SPANNING MAJOR PORTS, HARBORS, AND WATERWAYS

Ports included are those where commodity movements in 1976 exceeded 200,000 tons. The major ports, harbors, and waterways listed service oceangoing vessels as well as other traffic. Geographically, this listing begins with Maine and ends with the southeast coast of Florida. Major waterways are defined arbitrarily as 30 ft or more in depth.

Port/Harbor Waterway	Commerce in Short Tons	Bridge Name and/or Location	Date Permit/Completed	Bridge Owner	Miles Above Mouth	Bridge Type	Bridge Traffic	Clearances Horizontal	Clearances Vertical Low Water	Clearances Vertical High Water	Navigational Channel Depth
Portland, Portland Harbor, Fore River	25.4 million	Portland Bridge S. Portland, ME	Aug '14	Maine	1.5	Bascule	Highway	100	40	31	Over 40
Portland, Portland Harbor, Fore River	25.4 million	Veterans Memor'l Bridge, U.S. 1 Portland, ME	Apr. '54	Maine	3.0	Fixed	Highway Railroad	101	19	10	Over 40
				Boston & Maine Railroad	3.0			40			
Portsmouth, Piscataqua River	3.1 million	Kittery, ME to Portsmouth, NH Badgers Is. to Kittery, ME	Dec. '20	ME, NH, U.S. Govt.	3.5	Vertical Lift	Highway	260 Open	27 158	19 150	35-40
Portsmouth, Piscataqua River	3.1 million	Portsmouth, NH to Kittery, ME	Jul. '64	ME, NH	4.0	Vertical Lift	Highway	200 Open	18 143	10 135	35-40
		Second Channel	Jul. '64	ME, NH	4.0	Retract-able	Highway Railroad	70 Open	13 44	5 36	
Portsmouth, Piscataqua River	3.1 million	Portsmouth, NH to Kittery, ME	Dec. '66/Oct. '72	ME, NH	4.5	Fixed	Highway	440	143	135	35-40
Boston, Mystic River	26.2 million (Boston Harbor)	Chelsea - Charlestown, Massachusetts	May '47	Mystic River Bridge Auth.	0.1	Fixed	Highway	575	144	135	28-35

Port/Harbor Waterway	Commerce in Short Tons	Bridge Name and/or Location	Date Permit/Completed	Bridge Owner	Miles Above Mouth	Bridge Type	Bridge Traffic	Clearances: Horizontal	Clearances: Vertical Low Water	Clearances: Vertical High Water	Navigational Channel Depth
Boston, Chelsea River	26.2 million (Boston Harbor)	P. J. McArdle Bridge, E. Boston –Chelsea, MA	May '46	Boston	0.3	Bascule	Highway	175	30	21	28-35
Boston, Chelsea River	26.2 million (Boston Harbor)	Chelsea Street Bridge, E. Boston –Chelsea, MA	Dec. '35/Jul. '37	Boston	1.2	Bascule	Highway	96	19	9	28-35
Narragansett Bay, East Passage	4.7 million	Jamestown-Newport, RI	Dec. '63/Oct. '70	RI Turnpike and Bridge Auth.	4.0	Fixed	Highway	1,500	198	194	80+
Fall River, Mt. Hope Bay	4.7 million	Bristol-Portsmouth, RI	Oct. '27/Oct. '29	Mt. Hope Bridge Company	0.0	Fixed Suspension	Highway	585	139	135	35-40
Fall River, Taunton River	4.7 million	Braga Bridge, Somerset-Fall River, MA, I-195	Jan. '60	Mass.	0.4	Fixed	Highway	400	139	135	35-40
Providence, Narragansett Bay, West Passage	8.6 million	Jamestown-North Kingston, RI	Feb. '39/Jul. '40	Jamestown Bridge Commission	5.7	Fixed	Highway	600	138	134	35-40
New London, Thames River	3.3 million	New London - Groton, CT	Jul. '16/Feb. '19	Penn Central Railroad	3.0	Bascule	Railroad	151	33	30	28-35
New London, Thames River	3.3 million	New London - Groton, CT	Mar. '41	CT	3.1	Fixed	Highway	200	137	135	28-35
New London, Thames River	3.3 million	New London - Groton, CT	Apr. '64	CT	3.1	Fixed	Highway	200	137	135	28-35
New Haven, New Haven Harbor, Quinnipiac River	11.0 million	Tomlinson Bridge, New Haven, CT	Jun. '22/May '25	CT	0.0	Bascule	Highway	125	18	12	28-35

Port/Harbor Waterway	Commerce in Short Tons	Bridge Name and/or Location	Date Permit/Completed	Bridge Owner	Miles Above Mouth	Bridge Type	Bridge Traffic	Clearances: Horizontal	Clearances: Vertical Low Water	Clearances: Vertical High Water	Navigational Channel Depth
New Haven, New Haven Harbor Quinnipiac River	11.0 million	CT Turnpike New Haven, CT	May '55	CT	0.0	Fixed	Highway	283	66	60	28-35
Bridgeport Bridgeport Harbor Johnsons Creek	3.2 million	I-95, Pleasure Beach, CT	Jan. '24/Jul. '24	Bridge-port	0.0	Swing	Highway	70	13	7	35-40
Bridgeport, Yellow Mill Channel	3.2 million	Bridgeport, CT, I-95	Aug. '26	Bridge-port	0.3	Bascule	Highway	82	17	11	35-40
Bridgeport, Yellow Mill Creek	3.2 million	Bridgeport, CT, US 1	May. '55	CT	0.4	Fixed	Highway	100	46	40	35-40
Port of NY, NJ, NY Harbor	179.5 million	Verrazano Narrows Bridge, Staten Island, Brooklyn		Port Authority NY/NJ		Fixed	Highway	4,000+	222	217	45
Kill Van Kull		Bayonne Bridge Bayonne, NJ	Dec. '27/Nov. '31	Port Authority of NY	1.5	Fixed	Highway	1,640	155	150	35
Newark Bay		Elizabeth - Bayonne, NJ East Channel	Sep. '24/Nov. '26	Central Railroad of NJ	0.7	Vertical Lift	Railroad	134 Open	39 139	35 135	35
Newark Bay		Elizabeth - Bayonne, NJ West Channel	Sep. '24/Nov. '26	Central Railroad of NJ	0.7	Vertical Lift	Railroad	216 Open	39 139	35 135	35
Newark Bay		Newark-Bayonne, Turnpike Bridge	Mar. '53	NJ	4.0	Fixed	Highway	585	139	135	35
Newark Bay		Newark-Bayonne-Lehigh Valley	Jan. '27/Jan. '30	Penn Central Railroad	4.3	Vertical Lift	Railroad	300 Open	39 139	35 135	35

Port/Harbor Waterway	Commerce in Short Tons	Bridge Name and/or Location	Date Permit/Completed	Bridge Owner	Miles Above Mouth	Bridge Type	Bridge Traffic	Clearances Horizontal	Clearances Vertical Low Water	Clearances Vertical High Water	Navigational Channel Depth
East River		Brooklyn Bridge, New York City	1869	NY City	0.8	Fixed Suspension	Highway Railroad	1,350	136	127	35-40
East River		Manhattan Bridge New York City	Jan. '05/Dec. '09	NY City	1.1	Fixed Suspension	Highway Railroad	1,200	144	134	35-40
East River		Williamsburg Bridge, NY City	Sep. '95/Dec. '03	NY City	2.3	Fixed Suspension	Highway	1,536 Railroad	140	133	35-40
Arthur Kill		Outerbridge Crossing, Stat. Isl. Perth Amboy, NJ	Jul. '26/Jun. '28	Port of NY Authority	2.0	Fixed	Highway	675	148	143	35
Arthur Kill		Goethals Bridge, Staten Island - Elizabeth, NJ	Nov. '25/Jun. '28	Port of NY Authority	11.5	Fixed	Highway	617	142	137	35
Arthur Kill		Staten Island - Elizabeth, NJ	Sept. '52	B&O Railroad	11.6	Vertical Lift	Railroad	500 Open	35 139	31 135	35
Penn Manor, PA, Delaware River	6.3 million	Florence, NJ	Jun. '52/May '56	PA & NJ Turnpike Commission	121.2	Fixed	Highway	550	141	135	35-40
Penn Manor, PA, Delaware River	6.3 million	Bristol-Burlington, NJ	Dec. '28/1931	Bur-lington County	117.8	Vertical Lift	Highway	500 Open	68 140	62 134	35-40
Philadelphia, Delaware River	50.6 million	Tacony, PA - Palmyra, NJ	Dec. '27/1929	Bur-lington County	107.2	Bascule	Highway	240	59	53	35-40
Philadelphia, Delaware River	50.6 million	Betsy Ross Bridge, Delair NJ-Philadelphia	Aug. '68	Dela-ware Riv. Port Auth.	104.8	Fixed	Highway	500		135	35-40
Philadelphia, Delaware River	50.6 million	Delair, NJ	Nov. '56/Aug. '61	Penn Central Railroad	104.6	Vertical Lift	Railroad	500 Open	55 141	49 135	35-40

Port/Harbor Waterway	Commerce in Short Tons	Bridge Name and/or Location	Date Permit/Completed	Bridge Owner	Miles Above Mouth	Bridge Type	Bridge Traffic	Clearances: Horizontal	Clearances: Vertical Low Water	Clearances: Vertical High Water	Navigational Channel Depth
Philadelphia/ Camden, Delaware River	59.4 million	Ben Franklin Bridge, Camden Phila. US 130-30	Sept. '21/1926	Delaware Riv. Port Auth.	100.2	Fixed	Highway	1,686	135	129	35-40
Philadelphia/ Camden, Delaware River	59.4	Walt Whitman Bridge, I-76, Packer Avenue, Philadelphia	Feb. '53/May '57	Delaware Riv. Port Auth.	96.8	Fixed Suspension	Highway	1,930	145	139	35-40
Paulsboro, NJ, Delaware River	26.2 million	Commodore Barry Bridge, Chester, PA, US 322	Sept. '64	Delaware Riv. Port Auth.	81.4	Fixed	Highway	1,600	185	179	35-40
Marcus Hook, Wilmington, Delaware River	28.7 million 2.7 million	Delaware Memorial Bridge 1 Pigeon Pt., DE	Mar. '47/Aug. '51	Del.	68.9	Fixed Suspension	Highway	2,000	180	175	35-40
Marcus Hook, Wilmington, Delaware River	28.7 million 2.7 million	Delaware Memorial Bridge 2 Pigeon Pt, DE	Jul. '63/Apr. '69	Delaware Riv. Port Auth.	68.9	Fixed Suspension	Highway	2,140	180	175	35-40
Chesapeake & Delaware Canal	50.0 million	Reedy Point, DE	/Nov. '68	U.S.	1.0	Fixed	Highway	584		135	35
Chesapeake & Delaware Canal	50.0 million	St. Georges, DE	/May '42	U.S.	4.5	Fixed	Highway	523		135	35
Chesapeake & Delaware Canal	50.0 million	Canal, DE	/June '66	Penn Central Railroad	7.7	Vertical Lift	Railroad	548		135	35
Chesapeake & Delaware Canal	50.0 million	Summit, DE	/Mar. '60	U.S.	9.7	Fixed	Highway	586		135	35
Chesapeake & Delaware Canal	50.0 million	Chesapeake City, MD	/ '49	U.S.	13.9	Fixed	Highway	533		135	35

Port/Harbor Waterway	Commerce in Short Tons	Bridge Name and/or Location	Date Permit/Completed	Bridge Owner	Miles Above Mouth	Bridge Type	Bridge Traffic	Clearances Horizontal	Vertical Low Water	Vertical High Water	Navigational Channel Depth
Baltimore, MD, Patapsco River South Branch	52.5 million	Francis Scott Key Memorial Bridge-Soller Pt.-Hawkins Pt., I-695	Jun. '72	Mary-land	6.0	Fixed	Highway	1,100		185	Over 40
Baltimore, MD, Chesapeake Bay	52.5 million	William Preston Lane, Jr., Memor'l Bridge, US 50	Jun. '48/Sep. '53	Mary-land	138.0	Fixed	Highway	1,533	188	187	Over 40
Baltimore, MD, Newport News	52.5 million 13.3 million	Chesapeake Beach Cape Charles, VA (3 fixed spans)	Jul. '59/Apr. '64	Ches. Bay Bridge & Tunn. Comm.	6.0	Fixed	Highway Tunnel approach	70		23	Over 40
Norfolk, VA, Chesapeake Bay	50.0 million	Chesapeake Beach Cape Charles, VA	Jul. '59/Apr. '64	Ches. Bay Bridge & Tun. Comm.	6.0	Fixed	Highway Tunnel approach	300	77	75	Over 40
Hampton Roads, Newport News, Norfolk	63.3 million	Norfolk-Hampton (Twin) I-64	Feb. '55	Virginia	0.0	Fixed	Highway Tunnel Approach	45	12	10	Over 40
Hampton Roads, Newport News, Norfolk	63.3 million	Norfolk-Hampton (Twin) I-64	Jul. '71	Virginia	0.0	Fixed	Highway Tunnel approach	70	13	11	Over 40
Portsmouth/ Chesapeake, VA So. Branch Elizabeth River	8.0 million		/Oct. '47	Norfolk & Portsmouth Railroad		Vertical Lift	Railroad	300		142	35
Portsmouth/ Chesapeake, VA So. Branch Elizabeth River	8.0 million		/Oct. '28	City of Chesapeake		Vertical Lift	Railroad	220		145	35
Portsmouth/ Chesapeake, VA So. Branch Elizabeth River	8.0 million		/Oct. '75	Norfolk & Western Railroad	2.6	Vertical Lift	Railroad	220		135	35

Port/Harbor Waterway	Commerce in Short Tons	Bridge Name and/or Location	Date Permit/Completed	Bridge Owner	Miles Above Mouth	Bridge Type	Bridge Traffic	Clearances Horizontal	Clearances Vertical Low Water	Clearances Vertical High Water	Navigational Channel Depth
Chesapeake, VA So. Branch Elizabeth River	8.0 million		/Apr. '38	City of Chesapeake	5.8	Bascule	Highway	125			35
Chesapeake, VA So. Branch Elizabeth River	8.0 million		/Mar. '09	Norfolk & Western Railroad		Bascule	Railroad	125			35
Newport News James River		James River Bridge-US17	1981	Virginia		Vertical Lift	Highway	350		60 135	28-35
Hopewell, VA James River		Benjamin Harrison Bridge	1967	Virginia		Vertical Lift	Highway	300		30 135	28-35
Morehead City, NC, Newport Riv.	2.5 million	Morehead City, US 70	Sep. '62	NC	203.8 (IWW*)	Fixed	Highway	80	68	65	35-40
Morehead City, NC, Newport Riv.	2.5 million	Morehead City,	Oct. '47	Boston & Maine Railroad	203.8 (IWW*)	Bascule	Railroad	80	7	4	35-40
Wilmington, NC	7.9 million	Wilmington, US 17	Aug. '63/Oct. '69	NC	26.8	Vertical Lift	Highway	350 Open	68 138	65 135	35-40
Charleston, SC, Cooper River	9.6 million	Charleston, SC US 17	Sept. '61/May '66	SC	2.9	Fixed	Highway	700	155	150	28-35
Charleston, SC, Cooper River	9.6 million	Charleston, SC US 17	Feb. '28/Aug. '29	SC	3.0	Fixed	Highway	1,000	155	150	28-35
Savannah, GA, Savannah River	9.2 million	Eugene Talmadge Memor'l Bridge US 17	Dec. '51/Sep. '54	Coastal Highway District	14.9	Fixed	Highway	400	144	136	28-35
Brunswick, GA, Brunswick Riv.	1.7 million	Sidney Lanier Bridge, US 17	Jan. '48/Jun. '56	GA	4.9	Vertical Lift	Highway	250 Open	31 146	24 139	28-35

Port/Harbor Waterway	Commerce in Short Tons	Bridge Name and/or Location	Date Permit/Completed	Bridge Owner	Miles Above Mouth	Bridge Type	Bridge Traffic	Clearances Horizontal	Clearances Vertical Low Water	Clearances Vertical High Water	Navigational Channel Depth
Jacksonville, Florida	14.4 million	Mathews Bridge Jacksonville Term. Channel, US I-90	Jan. '50/Mar. '53	FL	21.4	Fixed	Highway	705	153	152	30-42
Jacksonville, Florida	3.7 million	Commodore Pt., Jacksonville	Dec. '62/Nov. '67	Jack-sonville Exp. Auth.	22.1	Fixed	Highway	960	143	141	30-42
Jacksonville, Florida	3.7 million	Main Street Bridge, Jackson-ville US 17	Oct. '65/Aug. '67	FL	24.7	Vertical Lift	Highway	350 Open	41 136	40 135	30-42

GULF COAST BRIDGES SPANNING MAJOR PORTS, HARBORS, AND WATERWAYS

Ports included are those where commodity movements in 1976 exceeded 200,000 tons. The major ports, harbors, and waterways listed service oceangoing vessels as well as other traffic. Geographically, this listing begins with the west coast of Florida and ends with the southern coast of Texas.

Port/Harbor Waterway	Commerce in Short Tons	Bridge Name and/or Location	Date Permit/Completed	Bridge Owner	Miles Above Mouth	Bridge Type	Bridge Traffic	Clearances Horizontal	Clearances Vertical Low Water	Clearances Vertical High Water	Navigational Channel Depth
Tampa, FL, Tampa Bay	39.9 million	Sunshine Skyway Bridge, US 19 (Twin)		Florida	0.0	Fixed	Highway	800		140	34-36
Mobile, AL Mobile River	31.5 million	Mobile, AL Cochrane (US 90)	Jan. '25	Alabama	2.9	Vertical Lift	Highway	300 Open	25 136	23 135	
New Orleans, LA, Miss. Riv.	156.0 million	Adjacent to Gr. New Orl. Brid.	Bridge under construction								
New Orleans, LA, Mississ-ippi River	156.0 million	Greater New Orleans Bridge, US 90	Sep. '54/Sep. '59	Miss. Riv. Brid. Auth.	95.7	Fixed	Highway	1,400	152	132	Over 40
New Orleans, LA, MRGO**	4.3 million	New Orleans, LA Paris Road (SR 37)	Nov. '64/Nov. '67	LA	13.0	Fixed	Highway	500	142	137	30-38
New Orleans, LA, Inner Harbor Navigation Channel	7.8 million	New Orleans, LA L&N Railroad	/'23	Port of New Orleans	2.9***	Bascule	Highway Railroad	93			26-41
New Orleans, LA, Inner Harbor Navigation Channel	7.8 million	New Orleans, LA I-10	/Dec. '65	LA	2.9***	Fixed	Highway	250		115 120 (mid 200')	26-41
New Orleans, LA, Inner Harbor Navigation Channel	7.8 million	New Orleans, LA U.S. 90 (Danziger)	/Apr. '32	LA	3.1***	Bascule	Highway	100		9	26-41
Miss. Riv. to Baton Rouge	66.7 million	Huey P. Long Bridge, New Orleans US 90	Dec. '30/Dec. '35	New Orleans	106.1	Fixed	Highway Railroad	750	170	150	Over 40

Port/Harbor Waterway	Commerce in Short Tons	Bridge Name and/or Location	Date Permit/Completed	Bridge Owner	Miles Above Mouth	Bridge Type	Bridge Traffic	Clearances Horizontal	Vertical Low Water	Vertical High Water	Navigational Channel Depth
Miss. Riv. to Baton Rouge	66.7 million	Luling-Destrahan, Louisiana	Jun. '72	St. John Bap., St. Chas. Par.	121.7	Fixed	Highway	1,200	154	133	Over 40
Miss. Riv. to Baton Rouge	66.7 million	Garyville, LA	Bridge under Construction (1981)			Fixed	Highway			139	Over 40
Miss. Riv. to Baton Rouge	66.7 million	Gramercy-Wallace, Louisiana	Bridge Under Construction			Fixed	Highway	750		139	Over 40
Miss. Riv. to Baton Rouge	66.7 million	Sunshine Bridge, Union-Donaldson-ville, LA, S 1	Jun. '55/Aug. '64	Ascen-sion & St. James Par.	167.5	Fixed	Highway	750	167	133	Over 40
Miss. Riv., Baton Rouge	66.7 million	Bat. Rouge-Port Allen, LA, I-10	Aug. '62/Nov. '67	LA	229.3	Fixed	Highway	1,120	165	125	Over 40
Lake Charles, LA, Calcasieu River	20.2 million	Lake Charles, LA, I-210, Rose Bluff Cutoff	Oct. '59/Dec. '63	LA	31.8	Fixed	Highway	250	133	125	35-40
Port Arthur, TX, Sabine-Neches Can. (GIWW)****	30.7 million	Port Arthur, Texas	Feb. '67/Oct. '70			Fixed	Highway	400	138	136	35-40
Port Arthur, TX, Neches River	30.7 million	Port Arthur, S 378	Dec. '35/Sep. '38	Texas	1.5	Fixed	Highway	600	176	172	35-40
Beaumont, TX, Neches River	43.9 million	Beaumont, TX	Feb. '40/Jul. '41	Kansas City So. RR	19.5	Vertical Lift	Railroad	200 Open	17 150	13 145	35-40
Houston, TX, Hous. Ship Chan.	89.9 million	Houston, TX Beltway 8	Nov. '76/Jan. '82	Texas Turnpike Authority	40.0	Fixed	Highway	500		175	Over 30
Houston, TX, Hous. Ship Chan.	89.9 million	Houston, TX I-610	Jan. '64/Aug. '73	Texas	47.2	Fixed	Highway	400	140	135	35-40

Port/Harbor Waterway	Commerce in Short Tons	Bridge Name and/or Location	Date Permit/Completed	Bridge Owner	Miles Above Mouth	Bridge Type	Bridge Traffic	Clearances Horizontal	Clearances Vertical Low Water	Clearances Vertical High Water	Navigational Channel Depth
Corpus Christi TX, Corpus Christi Channel	38.6 million	Industrial Channel, US 181	Dec. '54/Oct. '61	Texas	10.0	Fixed	Highway	300	140	138	40-47
Corpus Christi TX, Corpus Christi Channel	38.6 million	Tule Lake Channel		Corpus Christi	14.0	Vertical Lift	Highway Railroad	300 Open	11 140	9 138	40-47

PACIFIC COAST BRIDGES SPANNING MAJOR PORTS, HARBORS, AND WATERWAYS

Ports included are those where commodity movements in 1976 exceeded 200,000 tons. The major ports, harbors, and waterways listed service oceangoing vessels as well as other traffic. Geographically, this listing begins with the southern coast of California and ends with the northern coast of Washington.

Port/Harbor Waterway	Commerce in Short Tons	Bridge Name and/or Location	Date Permit/Completed	Bridge Owner	Miles Above Mouth	Bridge Type	Bridge Traffic	Clearances: Horizontal	Clearances: Vertical Low Water	Clearances: Vertical High Water	Navigational Channel Depth
San Diego, CA	2.1 million	Coronado Bay Bridge, San Diego Span 19-20	Jan. '65/May '70	CA	7.8	Fixed	Highway	600	199	195	30-40
		Span 20'21				Fixed	Highway	500	179	175	
		Glorietta Bay Channel, Span 14-15				Fixed	Highway	194	160	156	
Los Angeles-Long Beach Harbor, CA	30.9 million 31.4 million	Vincent Thomas Bridge, Los Angeles, CA	Apr. '59/Apr. '64	CA, Los Angeles	3.0	Suspension	Highway	1,150	169	165	50-50
Los Angeles-Long Beach	30.9 million 31.4 million	Henry Ford Ave., Long Beach, CA	Oct. '21/Oct. '24	Los Angeles	4.4	Bascule	Railroad	180	12	8	50-60
Los Angeles-Long Beach Harbor, CA	30.9 million 31.4 million	Terminal Island Freeway (Heim Br.) Long Beach, CA	Oct. '45/Jan. '48	Long Beach	4.5	Vertical Lift	Highway	180 Open	42	38 162	50-60
Los Angeles-Long Beach, CA	30.9 million 31.4 million	Gerald Desmond Br., Back Chan.			3.3	Fixed	Highway	300		155	50-60
San Francisco, San Fran. Bay	48.4 million	Golden Gate Br., San Fran.	June '31/'36	Golden Gate Br. Hwy Dist.	2.5	Suspension	Highway	4,028	238	232	29-45

Port/Harbor Waterway	Commerce in Short Tons	Bridge Name and/or Location	Date Permit/Completed	Bridge Owner	Miles Above Mouth	Bridge Type	Bridge Traffic	Clearances Horizontal	Clearances Vertical Low Water	Clearances Vertical High Water	Navigational Channel Depth
San Francisco, Oakland, San Fran. Bay	8.7 million	San Francisco-Oakland Bay Br. US 40 West Reach	May '32/'36	CA	8.9	Suspension	Highway	1,079	224	218	35
		Haywood-San Mateo, CA	1962/1966	CA	3.0	Fixed	Highway	600	142	135	
Richmond, San Fran. Bay	20.1 million	Richmond-San Rafael Hwy Bri.	Aug. '51	CA	3.0	Fixed	Highway				35
		Main chan. ctr span						1,000	190	185	
		Left, right span						480	173	168	
		East Chan. ctr span						465	123	118	
Carquinez Straits	24.2 million	Carquinez Straits Bridge	1953/1958 1924/1930	CA	0.2	Fixed	Highway	998	140	134	35
Carquinez Straits	24.2 million	Benicia-Martinez Bridges	Sept. '56/Oct. '62	CA	6.9	Fixed	Highway	440	141	135	35
			Mar. '29/Oct. '30	So. Pacific Trans.	7.0	Vertical Lift	Railroad	291	140	135	35
San Joaquin River	4.6 million	Antioch Bridge	Sep. '75/Sep. '79	CA	7.6	Fixed	Highway	400	142	135	35-40
Sacramento River	1.5 million	Rio Vista Bridge	Feb. '50/May '60	CA	12.8	Vertical Lift	Highway	270	149	146	35
Coos Bay	7.1 million	North Bend, OR	Jan. '13/Feb. '16	South Pac. RR	9.0	Swing	Railroad	197	19	13	28-35
Coos Bay	7.1 million	North Bend, OR US 101	Apr. '34/Jan. '36	Oregon	9.8	Fixed	Highway	515	126	120	28-35
Astoria, OR, Columbia River	4.1 million	Astoria, OR, to Point Ellice, WA (Main channel)	Sep. '58/Jul. '66	Wash. & Oregon	13.5	Fixed	Highway	1070	193	186	35-40

Port/Harbor Waterway	Commerce in Short Tons	Bridge Name and/or Location	Date Permit/Completed	Bridge Owner	Miles Above Mouth	Bridge Type	Bridge Traffic	Clearances Horizontal	Clearances Vertical Low Water	Clearances Vertical High Water	Navigational Channel Depth
Longview, Columbia River	9.2 million	Longview, WA, Rainier, OR	Nov. '27/May '30	WA	66.0	Fixed	Highway	1,085	187	176	35-40
Vancouver, WA, Columbia River	3.0 million	Vancouver, WA	Feb. '06/1908	Bur-lington No. RR	105.6	Swing	Railroad	200	37	21	35-40
Vancouver, WA, Columbia River	3.0 million	Vancouver, WA (Twin) Main Chan.	Jun. '54/Jul. '58	Oregon	106.5	Vertical Lift	Highway	263 Open	39 175	23 159	35-40
Columbia River		I-205 Bridge Portland, OR	1970 (under construction)	Oregon	112.7	Fixed	Highway	500	136	119	
Portland, OR, Willamette Riv.	21.5 million	St. Johns, OR	Jun. '29/Jun. '31	Mult-nomah Co.	5.9	Suspension	Highway	1,068	189	174	35-40
Portland, OR, Willamette Riv.	21.5 million	St. Johns, OR	Jun. '06/Dec. '10	Bur-lington No. RR	6.9	Swing	Railroad	230	55	39	35-40
Portland, OR, Willamette Riv.	21.5 million	Fremont Bridge, Portland, OR	Nov. '65/Nov. '73	Oregon	10.9	Fixed	Highway	928	163	147	35-40
Portland, OR, Willamette Riv.	21.5 million	Broadway Bridge Portland, OR	Mar. '10/1913	Mult-nomah Co.	11.7	Bascule	Highway	250	86	69	35-40
Portland, OR, Willamette Riv.	21.5 million	Steel Bridge Portland, OR	Nov. '09/1913	Union Pac. RR	12.1	Vertical Lift	Highway Railroad	205 Open	21 157	5 140	35-40 35-40
Portland, OR, Willamette Riv.	21.5 million	Burnside Bridge Portland. OR	Nov. 24/Jun. '26	Mult-nomah Co.	12.4	Bascule	Highway	205	58	41	35-40
Portland, OR, Willamette Riv.	21.5 million	Morrison Bridge Portland, OR	Feb. '55/Oct. '58	Mult-nomah Co.	12.8	Bascule	Highway	220	65	48	35-40
Portland, OR, Willamette Riv.	21.5 million	Hawthorne Bridge Portland, OR	Jun. '09/1911	Mult-nomah Co.	13.1	Vertical Lift	Highway	165 Open	47 157	30 140	35-40 35-40
Portland, OR, Willamette Riv.	21.5 million	Marquam Bridge Portland, OR	Apr. '61/Ap. '65	Oregon	13.5	Fixed	Highway	350	98	81	35-40

Port/Harbor Waterway	Commerce in Short Tons	Bridge Name and/or Location	Date Permit/Completed	Bridge Owner	Miles Above Mouth	Bridge Type	Bridge Traffic	Clearances: Horizontal	Vertical: Low Water	Vertical: High Water	Navigational Channel Depth
Portland, OR	21.5 million	Ross Island Bridge, Portland	Apr. '25/1927	Mult-nomah Co.	14.0	Fixed	Highway	350	84	67	35-40
Tacoma Harbor, City Wtrway	10.3 million	South 11th St., Tacoma, WA	Mar. '11/Oct. '13	Tacoma	0.6	Vertical Lift	Highway	200 Open	75 150	64 139	28-35
Tacoma Harbor, Blair Wtrway	10.3 million	East 11th St., Tacoma, WA	/1953	Tacoma		Bascule	Highway Railroad	150		14	28-35
Tacoma Harbor, Hylebos Wtrway	10.3 million	East 11th St., Tacoma, WA	Feb. '38/Jun. '39	Tacoma	1.1	Bascule	Highway	150	31	21	28-35
Duwamish River East and West Waterways		W. Spokane St., (dismantled following ship collision)	1924	Seattle	0.3(W) 1.3(E)	Bascule	Highway	145	53	42	34
Duwamish River East and West Waterways		W. Spokane St., South Span (to be replaced)	1930	Seattle	0.3(W)	Bascule	Highway	145	24 (43 at center)		34
Duwamish River West Waterway		Seattle	1971 (under construction)	Seattle	0.5	Fixed (twin)	Highway	380	151	140	34
East Waterway					1.4			210	118	107	34
Duwamish River East and West Waterways		Burlington Northern RR (to be replaced with vertical lift)	1917	Bur-lington	0.4(W) 1.3(E)	Bascule	Railroad	145	18	7	34
Honolulu, Honolulu Harbor	7.1 million	Slattery Bridge Honolulu, HI	May '59/Jul. '62	Hawaii	1.8	Bascule	Highway	250	18	15	28-35

*IWW - Intracoastal waterway
**Mississippi River Gulf Outlet
***From Mississippi River
****Gulf Intracoastal Waterway

Sources: U.S. Coast Guard (1980), Bridges Over Navigable Waters of the United States, Washington, D.C.: Government Printing Office); Institute for Water Resources (1980), National Waterways Study: Waterways System and Commodity Movement Maps (Ft. Belvoir, VA.: U.S. Army Corps of Engineers); National Oceanic and Atmospheric Administration (1982), United States Coast Pilot (Washington, D.C.: Department of Commerce); National Oceanic and Atmospheric Administration (1982) Nautical Chart Catalog (Washington, D.C.: Department of Commerce).

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This report provides a ~~Review~~ review of accident records of ship collisions with bridges in coastal ports and harbors, and of considerations important to preventing and mitigating such accidents--ship maneuverability in restricted waterways; dynamics of ship collisions with bridges; siting, design, geotechnical analysis and engineering criteria; protective and mitigative strategies; risk and hazards analysis. The report treats regulatory and institutional matters, and offers conclusions and recommendations.

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